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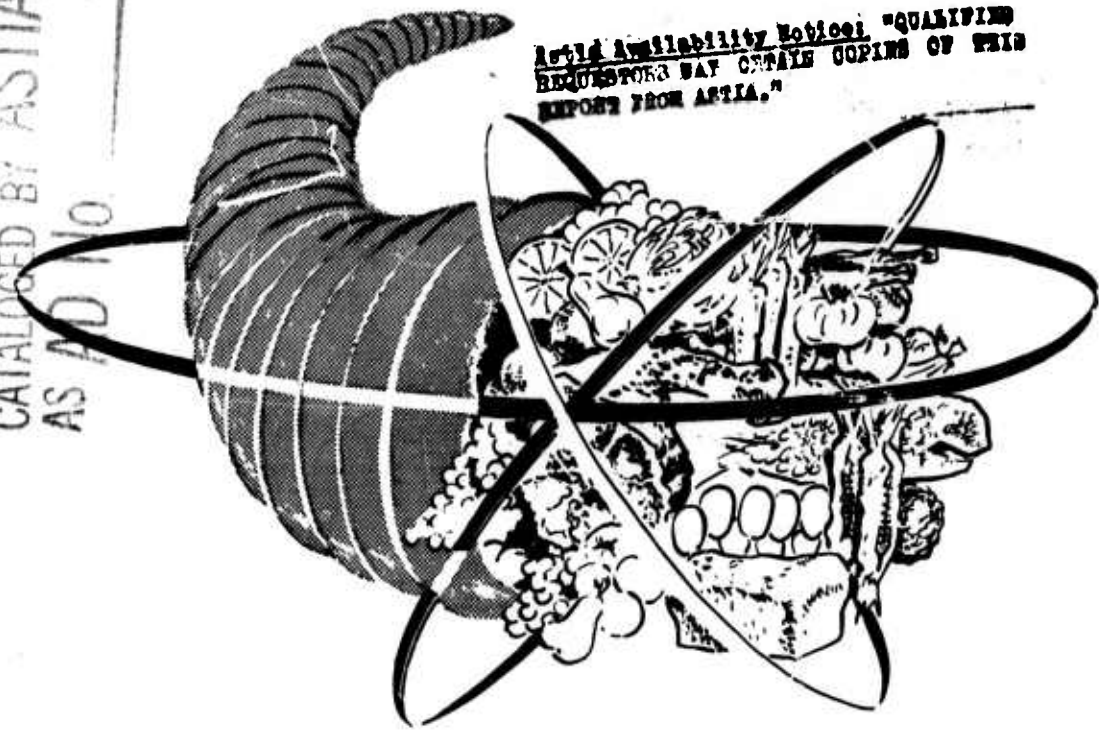
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PRESERVATION OF FOOD BY LOW-DOSE IONIZING ENERGY

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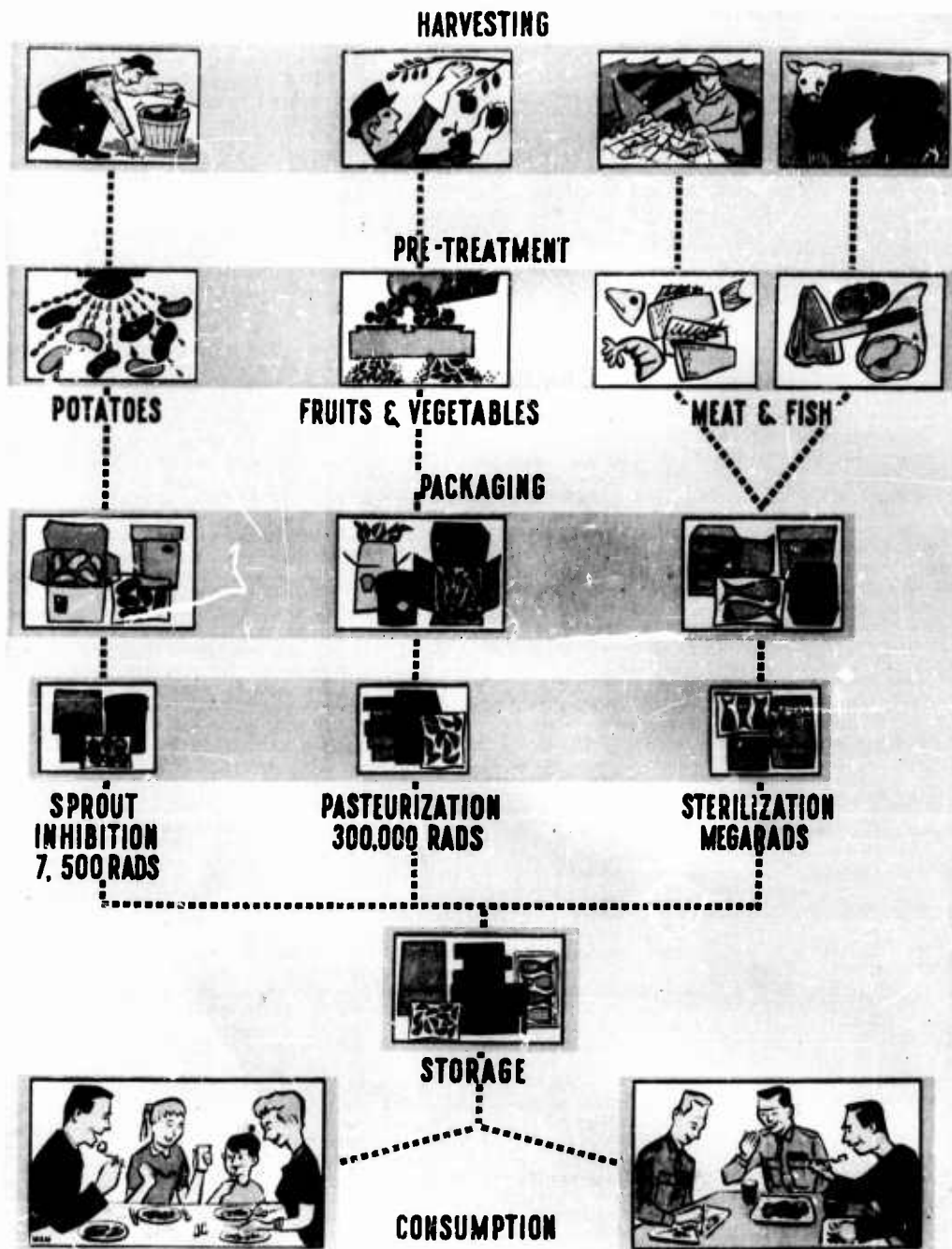
U S ARMY QUARTERMASTER
RESEARCH and ENGINEERING
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HEADQUARTERS
QUARTERMASTER RESEARCH AND ENGINEERING COMMAND
U. S. ARMY

PRESERVATION OF FOOD
BY
LOW-DOSE IONIZING ENERGY

QUARTERMASTER
RESEARCH AND ENGINEERING CENTER
NATICK, MASSACHUSETTS

JANUARY 1961



FOREWORD


As the centers of food consumption become increasingly removed from the centers of food production, marketing fresh food's becomes more and more complex. Maintaining food freshness from harvest through transportation and distribution to the point of consumption becomes increasingly important.

The tremendous advances in development and control of atomic energy in the last decade have given promise that a new method of food preservation by ionizing radiation may take a place alongside canning, freezing, and dehydration, in mankind's efforts to solve this growing problem of food preservation.

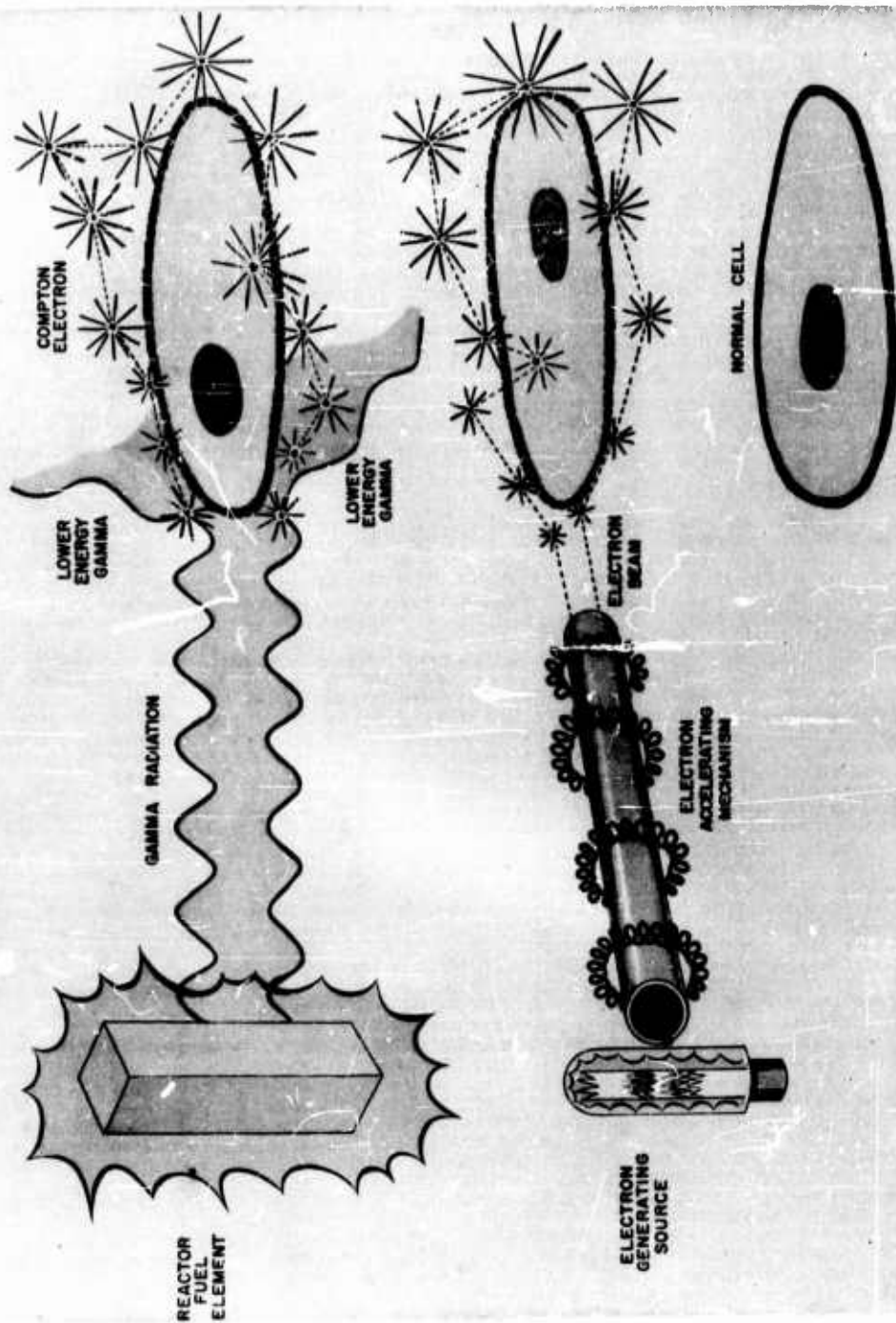
Under the country's Atoms-for-Peace Program, the use of ionizing radiations for the preservation of food was swept into the stream of national purpose, along with nuclear power, and the use of isotopes in industry, agriculture, and medicine. In particular, the Congressional Joint Committee on Atomic Energy has provided much encouragement for research along this channel. Since 1954, the Army Quartermaster Corps has been privileged to spearhead this program.

During recent years, non-military departments of the government began to assume increasingly important responsibilities in this program. It is gratifying to recognize the continuing and effective program stimulus of the Interdepartmental Committee on Radiation Preservation of Food, and the progressive and significant contributions of its other member agencies, including the Atomic Energy Commission; Departments of Agriculture; Interior, Health, Education, and Welfare; Commerce; State; Small Business Administration; and International Cooperation Administration. Appreciation is also extended to Industry for its cooperation and support.

It is hoped that this summary report of the progress made in the low-dose radiation preservation area of the Army Quartermaster Corps' program will be of assistance in furthering food radiation technology and attaining the ultimate goal -- widespread application of ionizing energy for extending the life of perishable food products.


MERRILL L. TRIBE
Brigadier General, USA
Commanding

MECHANISM OF IONIZING RADIATION



PREFACE

Laboratory research on irradiation preservation of foods, spear-headed by the Army Quartermaster Corps in close cooperation with the Office of the Surgeon General, has generated a vast amount of data encompassing basic scientific knowledge, wholesomeness, and product development.

As the result of this mass of knowledge the broad program has divided itself, essentially according to plan, into its natural components. The Army interest focuses on ration components which will provide superior subsistence and decrease logistical requirements. The National Program, guided principally by the U. S. Atomic Energy Commission, will exploit the civilian applications in low dose preservation. The two programs are working in close cooperation to derive maximum mutual benefits and practical potentialities of this most modern tool for food processing appear optimistic.

All who have contributed to this important program — technologists, engineers, scientists, military planners, administrators, and the many associates who have labored in various phases of this endeavor — are to be congratulated for their successes to date.

Also acknowledged are the efforts of those who, under the direction of Dr. F. P. Mehrlich, Scientific Director, U. S. Army Quartermaster Food and Container Institute of the Armed Forces, and Dr. A. W. Harvey, Special Assistant for Radiation, Headquarters, Quartermaster Research and Engineering Command, have contributed technical information for this report, including:

Capt. Roger W. Baker, V. C.	- meats and poultry products
Major Joseph P. Berg, Cml. C.	- wholesomeness, dosimetry, dose distribution, and induced radio-activity
Mr. Keith R. Clark	- dosimetry and dose distribution
Dr. Harry E. Goresline	- military application and significance
Dr. N. Grecz	- fruits and fruit products
SP/5 J. Hartman, V. C.	- vegetables
Dr. Fred Heiligman	- marine products

Miss Dorothy Ann Huber	- microbiological aspects
SP/7 Harry Lipsky	- wholesomeness
Major Sarah Niblack, WAC	- vegetables
Major Reuben Pomerantz, QMC	- ionizing energy sources and economic feasibility
Dr. George F. Shambaugh	- protection against insect damage
Mr. Morris Simon	- marine products and fruits
Mr. George Tripp	- packaging and protection against insect damage

Also acknowledged is the organizational and editorial support contributed by Dr. Martin S. Peterson, Miss Ruth Hennoch, and Mrs. Fonzell Vaughan.

The significant accomplishments made in the preservation of food by low-dose ionizing energy are the result of the coordinated efforts of all who have participated in this program.

Dale H. Sieling
 DALE H. SIELING
 Scientific Director

SUMMARY

The objectives of this program have been to develop a reservoir of basic knowledge which would determine the feasibility of preserving foods by ionizing radiation.

During the first seven years, research on preservation of food by ionizing energy has encompassed both high dosage and low dosage studies. The results from the former, particularly in regard to energy sources, dosimetry, dose distribution, induced radioactivity and wholesomeness, are almost entirely applicable to the latter. The major differences between the two dosage ranges lie in the sensory effects on the food items and in the packaging requirements. The purpose of this report is to delineate the progress made by the U. S. Army Quartermaster Corps in the low-dose area.

Among the meats, pork has responded best to irradiation processing in regard to flavor. At the low dose range, flavor change in pork is imperceptible. Chicken also is most promising. Beef appears acceptable at low dosage radiation ranges but still poses flavor problems at the high dosage levels. Sausage and luncheon meats demonstrate good potential.

Marine products are improved by low dose treatment so that increased distribution and marketing channels may be utilized. Items of special interest are haddock, flounder, clam meat, crab meat and shrimp. Radiation processing of fish could be of great importance in countries deficient in refrigeration facilities.

Vegetables, because of their delicate structure, are easily damaged by comparatively small dosages of radiation. Significant progress has been made in the radiation treatment of potatoes for sprout inhibition so that it is now only a question of economic comparison with other methods. Onions are also in a similar category. Shredded cabbage treated at 300,000 rad is an excellent product. Asparagus, snap beans, lima beans, broccoli, carrots and corn are among the more promising vegetables for radiation processing.

Fruits present a stimulating field for further study because they are preferred especially for their fresh natural flavors. Strawberries, grapes, peaches, tomatoes, and citrus fruits have shown promise at radiation dosage ranges between 200,000 and 800,000 rad. Advantages, among others, are the delays which are experienced in deterioration caused by molds and rotting. Packaging for specific storage conditions poses problems for individual commodities.

Protection induced by low dose radiation has proven to be effective against insect damage. Beneficial effects have been achieved with cereal grains, cereal products and military ration components. Mechanisms involved include destruction of adult insects, larvae, and eggs and interruption of reproductive cycles. Problems exist in packaging to prevent reinfestation.

The wholesomeness program was based largely on sterilized foods but did include four low-dose items; oranges, cabbage, potatoes and flour. With particular regard to wholesomeness, the results from high dosage treatments are anticipated to be applicable to low dosage irradiation of the same foods. This enormous nutritional and toxicity study is approaching its final phases including detailed histopathology and very long-term carcinogenic and enzymological experimentation.

Extensive studies relevant to induced radioactivity have been completed and some are continuing. The conclusions from high dosage studies are directly applicable to low dose work inasmuch as the induced activity if present would be in direct proportion to the dose. There is no radioactivity induced in the food products by any irradiation process contemplated to be used for food production.

Much progress has been made in primary, secondary and "go-no go" dosimetry. The use of the term "low-dose" dosimetry within the context of this report refers to measurement in ranges up to one megarad. It should not be confused with "low-level" dosimetry as used in measurement of radiation exposure in amounts of a few roentgens or fractions of a roentgen. Of equal importance to total dose is the distribution of the dose throughout the food product or package. Much progress has been made by studies of source geometry, scattering and absorbing devices and the theoretical and experimental studies with phantoms and food products.

Flexible packages have been studied with both high and low dose irradiation treatments. Results indicate that no serious problems exist in packaging in the low dose range. It is established, however, that specific packaging requirements will exist under certain storage conditions.

A review is presented of the current status of radiation sources. The conclusions are based on current knowledge and can form the basis for prediction as food processing by ionizing energy approaches nearer to commercial exploitation. Technical feasibility of this preservation method appears to be well established — economic feasibility appears promising, particularly in the low-dose applications.

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ABBREVIATIONS

Rad	quantity of ionizing radiation which results in the absorption of 100 ergs per gram of irradiated material at the point of interest.
Kilorad	1, 000 rads
Megarad	1, 000, 000 rads
Mev	million electron volts
Curies	units of radioactivity
AC	anaerobic count
SPC	Standard Plate Count
SGR	Sodium Graphite Reactor
MTR	Materials Testing Reactor

PART I

INTRODUCTION

In science, the development of a new process often begins with problem-solving. The application of ionizing radiations to the field of food preservation has been no exception.

For the first time in the history of food preservation, the unique method of processing by ionizing radiation promises to solve the problem of retaining the natural fresh qualities of perishable foods. In addition, ionizing radiation can inhibit insect infestations; control sprout formation in tuberous vegetables; and interrupt surface yeasts and molds in their proliferation. These are distinct gains.

Radiation preservation has been considered in terms of two dose levels, which are analogous to conventional processing methods for long-term and short-term storage:

a. A high-dose level, greater than 1.0 megarad and usually in the range of 2.0 to 4.5 megarad. This process has been termed sterilizing because it kills microorganisms, thereby providing a capability for long-term storage without refrigeration.

b. A low-dose level, 1 megarad or less. This process has been termed "pasteurizing" because it destroys or inhibits certain undesirable bacteria in food in much the same manner as conventional pasteurizing methods which are used for processing milk. "Pasteurization" provides a capability for extending the useful life of perishable food products under refrigeration.

Numerous radiation levels within the high- and low-dose ranges may be utilized for the preservation of various food products, as shown in the following table.

TABLE I Approximate Radiation Dose Ranges Required for the Preservation of Various Food Products

<u>Process</u>	<u>Rad</u>
Inhibition of sprouting carrots, onions, potatoes	4, 000 to 40, 000
Inactivation of trichina: steri- lization of trichina female	20, 000 to 50, 000
Insect disinfection of grains and cereals	100, 000 to 500, 000
"Irradiation pasteurization"	100, 000 to 1, 000, 000
Sterilization of foods	2, 000, 000 to 5, 000, 000
Enzyme inactivation	2, 000, 000 to 10, 000, 000

Inasmuch as this report concerns preservation of food by low-dose ionizing energy only, the 'pasteurization' terminology used throughout the text refers to radiation-pasteurization processes for food, and should not be confused with Pasteur's discovery for processing liquids. While the effects are essentially the same, the processing methods are entirely different.

Many foods either cannot be preserved by thermal processing, or are generally altered so that their acceptability is adversely affected. To preserve such foods by other methods is therefore desirable. In radiation processing, the temperature of the food is not increased beyond a few degrees. It is not the temperature that brings about the biological effects — it is the ionizing action of the penetrating energy that is responsible.

Interest in radiation processing of foods was stimulated shortly after World War II when it was discovered that conventional methods of supplying essential fresh meats and produce required a global refrigeration transport and storage capability far beyond that which could be maintained. Therefore, the greatest effort at that time was expended in high-dose levels which would minimize field refrigeration storage requirements.

It became evident in the early research stages that certain foods could be processed by low-dose radiation. Therefore, "pasteurizing" radiation has also been investigated rather extensively.

In August 1953, the Quartermaster Corps' plans for a Food Radiation Preservation Program were approved. Under this program a reservoir of basic knowledge has been developed.

In January 1954, an Army Task Group was organized to coordinate the important phases on wholesomeness and nutrition between The Quartermaster Corps and The Medical Corps.

Inasmuch as applied ionizing radiation techniques embraced new concepts regarding food preservation, a comprehensive wholesomeness program was conducted by The Quartermaster Corps in conjunction with The Office of The Surgeon General. This was probably one of the most extensive investigations of its kind ever undertaken.

This program, under military supervision, has been a truly cooperative effort, with many agencies working together toward a common goal. Government funds as well as those of industry and academic institutions have supported this program. Radiation services necessary for carrying out the investigations have been funded by the Government.

Beginning with 1954, the entire Government program on the treatment of food with ionizing radiations, except for a small amount of direct effort by the Atomic Energy Commission and the Department of Agriculture, was borne by the Army. However, the Department of Health, Education, and Welfare has served in a consultative and advisory capacity through its Food and Drug Administration. The Department of Interior has cooperated in preliminary screening experiments on the effects of ionizing radiation on selected fish products. The Department of Commerce has reported frequently on the work to interested trade associations, industry groups, and the general public.

During 1959 and 1960, 31 laboratories in universities, colleges and medical schools, 8 members of foundations and institutes, 4 government agencies, and 52 members of industry assisted in this program. Of the latter, 35 worked with their own funds, 17 used Government contract funds. The radiation sources that have been used for the processing include 6 electron sources, 3 cobalt sources, 4 reactor spent-fuel rod sources, and one X-ray source. Activity on such a broad front has developed a wealth of basic knowledge as well as a cadre of experienced workers in the food radiation preservation field.

Internationally, thorough interchange of scientific information has been achieved by direct contacts, and through the Office of European Economic Cooperation. Members of the Army team, including contractors, have participated in all international meetings held on irradiated foods in the United States, England, Canada, Poland, Switzerland, Argentina, and other countries.

Invaluable service and scientific advice on the various areas of this research program have been received from several sources, including: The Interdepartmental Committee on Radiation Preservation of Food with its several task groups; the Quartermaster Industry Advisory Committee on Radiation Preservation of Foods; the Quartermaster Corps-Army Medical Service Task Group on Radiation Sterilization of Foods; and the following Committees of the National Academy of Science, National Research Council: Committee on Radiation Preservation of Food, Committee on Microbiology of Food, Ad Hoc Committees on Potato Irradiation, on Dosimetry, and on Linear Accelerator.

Many substantial reports and publications in the field of radiation treatment of foods have resulted from this research and have become authoritative information in the scientific literature. One of the most definitive from a scientific point of view is the book entitled, Radiation Preservation of Food, authored by the U. S. Army Quartermaster Corps, published as U. S. Army Research and Development Series No. 1, 1 August 1957.

Inasmuch as complete background information and the technical detail up to the date of publication are contained in that monograph, they have not been repeated in this report, except by pertinent references.

This report presents progress in low-dose preservation of food which indicates numerous possibilities, particularly in the area of extending the holding period and maintaining the fresh qualities of food normally held under refrigeration. Also included are prospects for commercial potentialities.

PART II

ACTION OF LOW-DOSE IONIZING ENERGY IN INDIVIDUAL FOODS

At the outset, when pioneer research findings indicated the possibility of utilizing ionizing radiation for food preservation, very little was known about the physical, chemical, and biological effects of this process on foods.

Whereas the preservation action of conventional methods — drying, pickling, salting, smoking, freezing, and heating — were known to depend upon control of the molecular character of the system, ionizing radiations, utilizing energies of a magnitude never before used, have required extensive research.

It has been found that unique changes are brought about in foods exposed to ionizing radiations. When employed in relatively low amounts, the treatment inhibits the sprouting of certain tubers. With slightly higher amounts, insect life and disease-causing worms are killed. With much higher amounts, most microorganisms are killed and the chill shelf-life of many fresh foods can be extended significantly. At the highest levels utilized, all microbial life is destroyed and the food is freed from microbiological spoilage, even when subsequently kept at room temperatures, providing that it is adequately packaged.

Considerable research has been directed toward determining the sensory and microbiological effects of this process, as well as other related effects. Significant accomplishments made in analyzing the effects of low-dose ionizing energy on (1) meats and poultry products; (2) marine products; (3) vegetables; (4) fruits and fruit products; (5) miscellaneous items; and (6) protecting foods against insect damage are presented in the following six chapters.

CHAPTER 1

RADIATION PRESERVATION OF MEATS AND POULTRY PRODUCTS

The main advantage of low-dose radiation of meats and poultry products is that this preservation process inhibits microbial spoilage. Therefore, considerable research has been directed toward exploiting the microbiological aspects while retaining the desirable sensory characteristics of the processed items.

Due to the high consumption of beef, it took precedence over other meat products until it was definitely established that pork responds more favorably to radiation than beef.



Figure 1-1. The irradiation of pork not only extends its keeping qualities, but also maintains good color, aroma, and texture, without adversely affecting flavor.

Emphasis has been placed on extending the refrigerated life of meat products, either by partially reducing the microbial population or by extending the latent growth period of the micro-organisms.

The following analyses of research findings present both the lights and the shadows regarding low-dose radiation preservation of meats and poultry products:

1. PORK

One of the most significant accomplishments in low-dose radiation of meat products has been the discovery that ionizing radiations, both X-rays and Cobalt-60, successfully controlled worm parasites, including trichina larvae^{1, 10, 9}. This has been a long-standing problem in maintaining the wholesomeness of pork products.



Figure 1-2. The irradiation of pork products eliminates trichinosis contamination.

In stability tests¹, processing pork with 30,000 rad prevented trichina larvae from reaching maturity; they underwent a partial development in the host during the first 48 hours after irradiation.



Figure 1-3. Ham responds well to radiation preservation.

Ham that had been canned, irradiated at 500,000 rad, and held 5 months at room temperature, had good color and texture as well as a normal odor¹⁴.

Maximum storage life of raw ground pork, irradiated at 60,000 to 80,000 rad, was reported^{6,4} to be 10 days at 40° F. Threshold doses (doses tolerated without flavor change) for pork sausage links and sliced bacon were 1.0 megarad and 0.5 megarad, respectively.

It was concluded²⁶, after research on the keeping qualities of pork treated with gamma and cathode rays, that ionizing radiations caused some deterioration of the color of pork, but less than that observed in beef. At doses under 100,000 rad (cathode rays), however, the keeping time of pork was not extended appreciably, thus indicating the need for higher doses within the low-dose range (under 1 megarad).

In other tests²⁵, pork chops held at 45° F. without irradiation showed a putrefactive type of spoilage in 4-6 days. Samples irradiated to 25,000 and 50,000 rad became putrid in 12 days, while samples receiving 100,000 rad showed a yeast-type of spoilage in 12 days.

Vacuum-packed, sliced, fresh pork loin soured in 7-10 days at 40° F., whereas samples irradiated to a dose of 200,000 rad gave low counts for 18-20 days. Samples receiving doses of 400,000 and

800,000 rad showed low counts of 1,000 to 5,000 organisms per gram for the entire 39-day test period. However, a rancid odor became apparent before the end of the period³⁴. Precooking the same product increased the control storage-life to 28 days before it was spoiled by lactic-acid bacteria. Irradiation of the precooked samples to 250,000 rad extended this period to 75 days, when the spoilage organism was shown to be yeast³². The evidence suggested that acceptance of an irradiated product may become associated with or dependent upon rancidity of the fat rather than microbial spoilage.

Fresh pork sausage vacuum-packed in cans and stored at 38°-44° F. (a store type self-service cabinet) spoiled in 3-5 days with microbial populations of 10^6 - 10^7 organisms per gram. Samples irradiated to 50,000 rad showed no improvement over the control samples, but those given 100,000 and 200,000 rad were held 10 to 13 days before the bacterial population reached 10^5 organisms per gram and off-colors appeared. At 400,000 and 800,000 rad, the counts remained below 5,000 per gram for the 30-day test period although color changes were becoming apparent³⁴.

During experimental stability tests¹⁸, it was discovered that low-dose radiation at 100,000 rad, followed by thermal processing at a "pasteurizing" level, produced a canned ham that remained stable for an extended period at incubation temperatures, without developing anaerobic bacteria. After 30 days at 100° F., control-heated samples showed aerobic and anaerobic counts up to 6,100 organisms per gram. Hams irradiated with 100,000 rad before heating were negative for recoverable organisms of either type¹⁸.

The synergistic effects of combining antibiotic dips or sprays with radiation were tested and reports indicated that the extent of increased stability depended upon the food being tested^{2, 7, 28, 29, 30, 31, 32, 33, 39}.

2. VEAL

With respect to veal, irradiation and storage studies¹⁵ of ground calf meat (6-8 months old) indicated that fresh irradiated samples had a less desirable flavor than the nonirradiated. There were, however, encouraging aspects. A five-fold extension of the refrigerated shelf-life of pre-packaged meats was realized by treatment with 50,000 rad. At this dosage, little if any off-flavor, unnatural odor, or discoloration was noted²⁴. Color changes in meat have been reported for irradiation doses as low as 150,000 rad^{3, 5, 11, 12, 20, 21}. Storage data¹⁶ for 10 weeks at 32° F. indicated that a dose of 500,000 rad, or higher, stabilized the raw meat against bacterial decomposition during refrigerated storage.

3. BEEF

Pre-cooked, vacuum-packed, rib-eye steaks were irradiated with 20,000, 40,000 and 80,000 rad. Taste evaluations³⁶ showed the irradiated samples were acceptable up to 40,000 rad. The shelf life at 34° to 38° F. showed an extension of 7 to 18 days over the unirradiated control samples.

This process promises to extend the useful life of beef products, thereby reducing losses from spoilage.

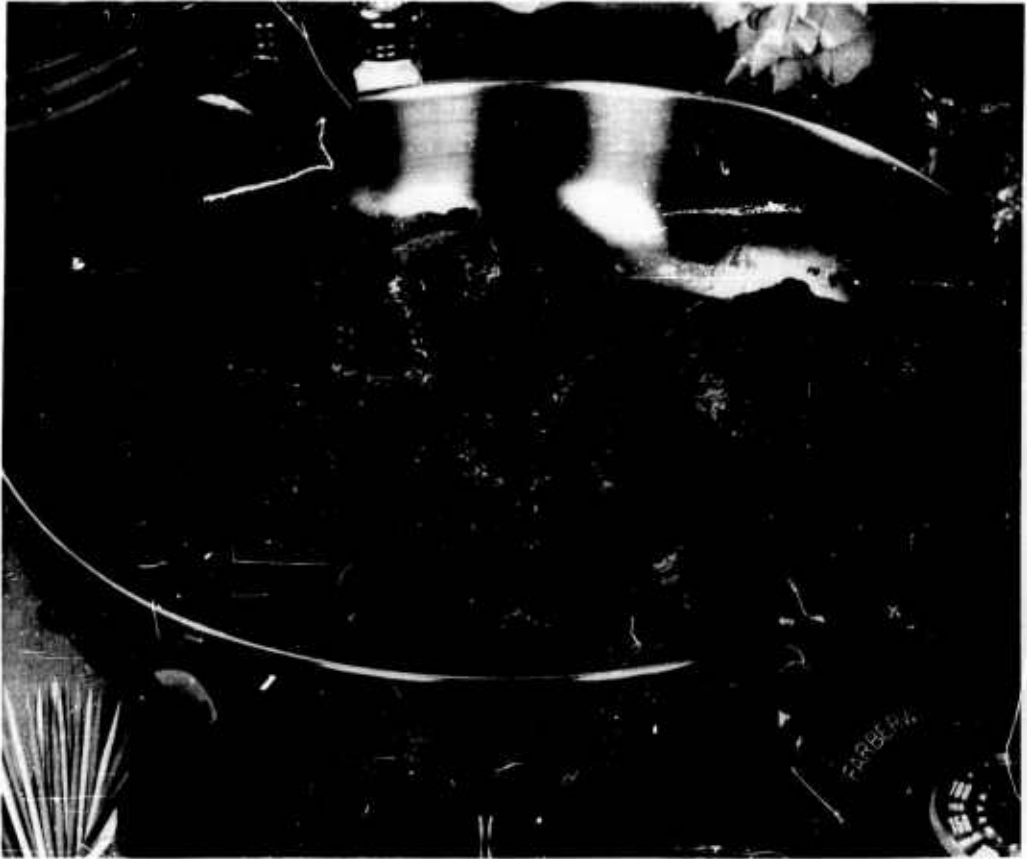


Figure 1-4 Pre-cooked steaks given 40,000 rad were well received by taste panels. "Pasteurization" processing extended the storage life 7 to 18 days over the unirradiated steaks.

In stabilization tests on raw rib-eye steaks held at 38° - 40° F., the microbial population increased to 10⁶ per gram in 7 days, but irradiation to 80,000 rad doubled the storage-life to 14 days. When precooked steaks were used for a repeat of this experiment, the storage-life was extended to 40 days by irradiation with either 40,000 or 80,000 rad³⁵.

In a study conducted at the U. S. Army Quartermaster Food and Container Institute for the Armed Forces, using pre-mortem epinephrine injection, round steaks were irradiated to 100,000 or 500,000 rad and stored at 40° F. All steaks receiving the lower dose in this experiment showed counts of 10⁶ per gram in less than one month's storage; whereas the counts on those from the higher dose level remained less than 300 per gram throughout the six-month test period⁸.

In tests on fresh, very lean ground beef (1-3% fat), which was used in lieu of normal hamburger (30-45% fat) because of reduced rancidity, the unirradiated control samples spoiled in 9 days at 40° F., or 3 days at 45° F. The shelf-life of samples irradiated with 100,000 rad was 11 days at 40° F., or 4 days at 45° F., and for those cans given 400,000 rad, it was more than 29 days at 40° F.³⁷.

The storage-life of frankfurters at 40° F. is approximately 7 days. This period can be extended to at least 30 days by irradiation with 100,000 or 400,000 rad¹³.

Chemical additives, used in conjunction with irradiation, have been investigated²³ and appear useful in producing a meat product that is more acceptable, both in shelf-life and sensory qualities than the corresponding product irradiated without the additives.

Lean ground beef with 0.5 and 2.0 ppm of added aureomycin, irradiated at 100,000 rad, underwent a marked extension of storage life at 40° F., as indicated by bacterial counts. In one set of experiments, it took the bacterial counts of the treated samples approximately one month to reach the initial count of the untreated ground beef from which they were made. Of eight antibiotics screened at the 1-5 ppm level in ground beef, aureomycin was the only one which showed a synergistic effect when coupled with irradiation²³.

In other tests⁶, it was asserted that irradiation to approximately 110,000 rad developed a better flavor in fresh ground beef than that of the unirradiated samples.

4. SAUSAGE PRODUCTS

Precooked pork sausages packed in air, nitrogen and under vacuum and then irradiated to 240,000 and 480,000 rad were evaluated three days after irradiation and found comparable in acceptability to the unirradiated controls. Those samples rating lowest were those packed in air and irradiated to 240,000 rad³⁷. Precooked pork sausages made from standard formula, 10% and 20% increase in spice (not salt and pepper), were treated at three irradiation levels; namely, 300,000, 450,000 and 600,000 rad by an Arco linear accelerator. Taste panel results indicated that all irradiated samples were acceptable after five days of storage at 40° F. There seemed to be a slight loss in flavor in the samples containing 20% added spice³⁸.

Frankfurters given 250,000 rad of cathode rays were still good after 3 months' storage at 36°- 40° F.²² Irradiation doses above 250,000 rad however, impaired the acceptability of bologna, sliced or whole.

Vacuum-packed frankfurters had a much better color and texture after prolonged storage than cellophane-wrapped samples, even though stored under quite humid conditions. All frankfurters after irradiation showed some color changes, including those receiving only 50,000 rad. This was evident immediately after radiation and persisted throughout the storage period¹⁹.

The effect of heat treatment upon acceptability of ground meats has been studied. Heating ground pork (or beef) prior to radiation resulted in products which were not markedly different, on a sensory basis, from those heated after irradiation. With respect to odor, all heated-irradiated products were superior to raw-irradiated products²⁷.

5. POULTRY

Chicken meat was subjected to various pre-irradiation treatments and then irradiated at dosages ranging from 100,000 rad to 5,000,000 rad with gamma rays or electrons from a linear accelerator. Doses under 100,000 rad did not affect acceptability. Evaluation of the irradiated samples by panels of trained judges revealed that chicken irradiated at dosages above 100,000 rad could easily be distinguished from the unirradiated control samples, regardless of whether pre-irradiation heat treatment was employed or the material was irradiated in air, nitrogen, under vacuum, or in the frozen or thawed state¹⁷.

Microbiological research studies³⁰ on fresh meats have indicated that the Pseudomonas and Achromobacter species, which are ordinarily associated with spoilage of fresh meats under refrigeration, appear to be well controlled for limited periods by low-dose irradiation of approximately 100,000 rad. When spoilage occurs, yeasts occasionally have been responsible. If the storage period was more than a month, some products sampled at various intervals showed a progression of microbial types. For example, in one series of experiments (using a standard plate count of 10^6 organisms per gram as a criterion of spoilage), the initial flora of cut-up chicken parts irradiated to 100,000 rad was predominantly Candida-type filamentous yeast; after 12 days at 40° F. these appeared to be replaced by Pseudomonas type Gram-negative rods. At about 15 days lactic-acid type organisms became predominant and persisted until about 33 days after which the Gram-negative flora reappeared. It was not until 40-42 days that spoilage was eventually produced.



Figure 1-5 Irradiated chicken, included in menus prepared for Taste Testing Panels, received acceptable ratings.

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CHAPTER 2

RADIATION PRESERVATION OF MARINE PRODUCTS

In addition to supplying the needs of the U. S. Military Forces, fish and fish products are generally recognized as having great potential for supplying the food needs of exploding world populations. Sea foods are extremely perishable, therefore have a relatively low consumption, due largely to the costly problems involved in distributing them in prime condition to inland markets.

Through an extensive and cooperative research program, significant progress has been made in developing "pasteurizing" processes that benefit these foods, and in addition, provide advantages to the processors, distributors, and consumers. A recent report indicated that sea foods probably will be among the first to be commercially pasteurized.

Items which showed promise of benefit through low-dose radiation processing include haddock fillets, clam meat, crab meat, flounder, and shrimp.



Figure 2-1. In low-dose "pasteurization" experiments, raw and cooked shrimp, which normally keep only 5 to 10 days, rated as well after 13 weeks at normal refrigerated temperatures as the frozen unirradiated samples.

The high incidence of psychrophilic organisms in raw fish, even at normal refrigerated temperatures (32° to 40° F.) has been a continual problem. Marketing fresh frozen fish involves costly processing, storing, distributing, and retailing. Inasmuch as the bacteria primarily responsible for spoilage are destroyed by relatively low doses of ionizing radiations, marine foods are exceptionally well adapted to preservation by radiation.

The U. S. Army Quartermaster Food and Container Institute for the Armed Forces, through its research program on low-dose irradiation of fish and fish products, has obtained much information through cooperative efforts with a number of agencies and organizations.*

In the early stages of the Quartermaster Corps program on radiation preservation of foods, many items were screened to determine (1) the gross effects of irradiation on all types of foods^{1, 2}, and (2) the adaptability of foods to radiation processing³. Significant findings on these and subsequent studies include:

Shrimp: Shrimps were purchased frozen and kept in the frozen state except during pre-irradiation packaging and for the period during which the cans were immersed in the radiation canal at the Materials Testing Reactor (MTR), Idaho Falls, Idaho⁹. Shrimp given doses of 0.1 and 0.5 megarad, boiled and chilled, were compared with the corresponding unirradiated product by a panel of 16-20 judges. Average scores on a 9-point hedonic scale, ranging from (1) dislike extremely to (5) neither like nor dislike to (9) like extremely, indicated no preference change at 0.1 megarad, and a slight loss at the higher dose level.

In other experiments³, frozen, cooked, peeled and deveined Jumbo Gulf shrimp, were packed in cans and irradiated under the conditions described for oysters. Unirradiated control samples spoiled after 16 days at 34° - 36° F., whereas shrimp exposed to 0.1, 0.25 and 0.5 megarad were acceptable up to 72, 96, and 110 days' storage, respectively.

* Organizations which have engaged in research on low-dose radiation of marine products include: University of California, Davis, Cal., (DA-129-QM-256); Whirlpool Corp., St. Joseph, Mich. (QMR&E, Natick, No. 49); U. S. Dept. of Interior, Fish and Wildlife Service - Fishery Technology Labs., College Park, Md., E. Boston, Mass., Seattle, Wash.; and these laboratories under contract to the USDI, Fish and Wildlife Service: Mass. Institute of Technology, Cambridge, Mass.; Florida State Univ., Tallahassee; Oregon State College, Corvallis; and Food Chem. and Res. Lab., Inc., Seattle, Wash.

Raw haddock, halibut, and scallops were purchased and kept frozen, except during periods of packaging and irradiation at doses up to 0.75 megarad¹⁰

Haddock and halibut retained their original preference at doses up to 0.15 megarad after which they declined with rising doses. Scallops, on the other hand, lost little preference even at the highest dose employed.

In studying the relationship of fat oxidation in irradiated foods to flavor, color, and vitamin changes, A. L. Tappel and Associates¹² examined the effects of low-dose irradiation on the color, odor, taste, and retention of certain vitamins in a number of fish species. Samples of raw fish packaged in flexible films were electron-irradiated and examined after storage for a week in wet ice. Findings include:

Catfish given 0.5 megarad had abnormal odor although color and taste were considered normal. Codfish at 1 megarad had a fresh-like odor; color and taste were normal. Halibut was normal in color and taste after irradiation at 0.25 megarad. Its odor, although not like that of spoiled fish, was not normal.

Raw Shrimp treated with 0.5 megarad was described as normal in color, taste, and odor except for a slight iodine-like quality. The shrimp acquired a bleached appearance when cooked, suggesting some loss of the carotenoid pigments.

Sole, as with other fish products tested at 0.5 megarad, produced some off-odors, although color and taste appeared unaffected.

Salmon, of the various species examined, suffered the greatest loss in sensory quality. At 0.5 megarad the odor was described as slightly off; and severe bleaching was also noted. Chemical assay related the color loss to destruction of the muscular carotenoid astaxanthin, with 44 to 46 percent of the pigment lost at this dose level. The extreme lability of its typical color prompted additional experimentations. Samples of King Salmon were frozen in No. 2 cans and exposed to doses of 0.2, 0.5, and 1.0 megarad at the Materials Testing Reactor Gamma Facility. Again, substantial losses in carotenoid pigments were noted at all doses.

It was suggested that the extreme lability of astaxanthin to radiation dosage may be an oxidative reaction involving the unsaturated fatty acids known to occur in fish.

Frozen ground tuna exposed to gamma radiations at the Materials Testing Reactor Facility gave the following results:

TABLE 2-1. Sensory Appraisal of Irradiated Tuna

<u>Dose (Megarad)</u>	<u>Odor</u>	<u>Color</u>
0	Fishy	Light brown (normal)
0.2	Fishy	Light brown (normal)
0.5	Fishy	Light brown (normal)
1.0	Slightly burned	Light red-brown

Salmon, lake trout, halibut, and tuna fish which had been frozen and nitrogen-packed were given additional sensory tests. Lake trout and halibut were acceptable at doses up to 1 megarad; salmon and tuna were acceptable at the 0.5 megarad level. The color of all samples was acceptable, although salmon showed some fading at the 0.5 megarad level.

The lability of thiamine in fish to ionizing irradiation is illustrated by the following table:

TABLE 2-2. Retention of Thiamine in Irradiated Fish

<u>Species</u>	<u>Percent Retention at Indicated Doses</u> <u>(Megarads)</u>			
	<u>0</u>	<u>0.2</u>	<u>0.5</u>	<u>1.0</u>
Salmon	100			46
Lake Trout	100		37	22
Halibut	100			14
Tuna Fish	100	76	67	35

Oysters were tested at Florida State University⁴, and it was discovered that doses up to 0.63 megarad were insufficient to retard spoilage in fresh oysters refrigerated at 41° F. Radiation at this level caused little change in appearance in the oysters, but the liquor was more turbid than the non-irradiated controls. The odors during storage progressed from fresh, to stale, to slightly sour in all samples, but the characteristic odors were more intense in the irradiated lots. Development of off-odors was not prevented by anti-oxidants or free

radical acceptors. In other experiments with live oysters, it was learned that irradiation could not be effectively employed for opening the shells. Doses of 0.32 megarad were required to kill the oysters and shell opening did not occur until approximately seven hours after irradiation. In experiments performed by the Whirlpool Corporation³, raw Eastern oysters packed in ice were obtained approximately 48 hours after harvesting, repacked in cans under 15 inches vacuum, and gamma irradiated at about 40° F. to doses of 0.23, 0.46, 0.93, 1.4, and 2.3 megarad. The irradiated products were appraised by a panel of 24 judges at several intervals during storage at 34° - 36° F. Non-irradiated oysters were unacceptable after 22 days of storage. Oysters irradiated at doses upwards of 0.93 megarad showed approximately three-fold increase in refrigeration shelf-life. At all irradiation levels, the oyster liquid was dark beige in color, cloudy, and watery; un-irradiated frozen controls were slightly translucent, bluish, and more viscous. The irradiated oysters had a strong, metallic odor, had lost firmness, and had become shrunken and fragmented as storage progressed. The degree of change increased with irradiation level. Bacterial counts at all radiation levels were initially less than 300 per gram and remained so during storage. This suggested that spoilage was autolytic rather than bacterial.

Haddock: In other tests, raw haddock, purchased frozen and kept frozen except for periods during packaging and irradiation at the Materials Testing Reactor, were irradiated employing three dose rates: 10^5 rad per hour, 5×10^5 rad per hour, and 5×10^6 rad per hour. Hedonic scale evaluations of the baked products indicated declining preference with rising doses. There appeared to be no effects from flux variation within the limits employed.

Studies Sponsored by Fish and Wildlife Service, U. S. Dept. of Interior

In studies conducted at Massachusetts Institute of Technology⁸, raw and cooked haddock, mackerel, ocean perch, and cooked lobster, were given doses of 0.25, 0.50, 0.75, and 1.0 megarad, and stored at two temperature ranges (36° - 40° F. and 32° - 33° F.).

Organoleptic tests on mackerel showed no difference between irradiated and control samples after 3 weeks at 32° - 40° F. Following this, flavor rating declined due in part to proteolytic enzyme activity and increases in trimethylamine (TMA) content. Samples irradiated above 0.5 megarad were bacteriologically sound. Cooked mackerel was more stable than the uncooked product. Irradiated haddock was acceptable after 56 days at all dose levels. The trimethylamine content of haddock was directly related to irradiation level, i.e., the higher the dosage the more TMA detected. No enzyme proteolysis was observed, and all irradiated haddock samples were rated lower than frozen controls.

Irradiated perch was as acceptable as unirradiated samples at all dose levels, and no changes in trimethylamine and tyrosine levels were detected after 6 weeks' storage at 36° - 40° F. In all studies, fish spoilage was unrelated to putrefactive bacteria. The results of the Massachusetts Institute of Technology studies are reflected in the following table:

TABLE 2-3. Summary of Work Done on Irradiated Marine Products at Massachusetts Institute of Technology

<u>Species</u>	<u>Treatment Before Irradiation</u>	<u>Irradiation Dose (Megarad)</u>	<u>Optimum Storage In Days</u>	<u>Life Temp. (° F)</u>	<u>Max. Acceptance dose (Megarad)</u>	<u>Best Storage Dose at 35° F. (Megarad)</u>
Mackerel	Frozen, Vacuum No. 2 Can	0.5 - 1.0	35-56	40	1.0	0.75
Mackerel	Blanched 5 min. 212°F. Frozen, Vacuum	0.25 - 1.0	77-126	36	1.0	0.75
Haddock	Frozen, Vacuum	0.75	39-49	36°-40°	1.0	0.75
Haddock	Blanched 5 min. 212° F. Frozen, Vacuum	0.75	49-63	36°-40°	1.0	0.75
Ocean Perch	Frozen, Vacuum	0.75	28	36°-40°	0.75	0.75
Ocean Perch	Frozen, Blanched	0.75	7-56	36°-40°	0.75	0.50
Lobster Meat	Polybags Cooked	0.5	28	32°-40°	0.5	0.5

The USDI - Fishery Technological Laboratory reports⁵, on work with fresh fish (12-36 hours old), indicate that irradiation processing of vacuum-packed fish and shell fish can extend their refrigerated shelf-life by at least 30 days at 35° F. Detailed results of the fresh fish studies are presented in table 2-4.

TABLE 2-4. Summary of Work Done at USDI - Fishery Technological Lab., East Boston, Mass.

<u>Species</u>	<u>Treatment Before Irradiation</u>	<u>Irradiation Dose (Megarad)</u>	<u>Optimum Storage Life 35° F. Temp. Days</u>	<u>Max. Acceptance Dose (Megarad)</u>	<u>Best Storage Dose at 35° F. (Megarad)</u>
Cod	Raw	0.25	94	1.0	0.25
	Fillets	0.5	31		
Cod	Fillets	0.5	118	2.0	0.5
	Blanched 140° F., 5 min.	1.25	118		
Pollack	Raw	0.25	21	0.75	0.25
	Fillets	0.5	14		
		1.0	7		
Pollack	Blanched Fillets			1.0	
Whiting	Raw			0.25	
	Fillets				
Whiting	Blanched Fillets			1.0	
Butterfish	Raw	0.25	49	0.75	0.5
	Drawn	0.5	49		
Butterfish	Blanched	0.25	38	2.0	0.5
	Drawn	0.5	38		
Flounder (Blackback)	Raw Fillets			0.75	
Finan	Skinned	0.75	215	1.5	0.75
Haddie	Fillets	1.5	215		
Kippered Herring	Whole	0.25	141	2.0	0.50
		2.0	141		
Lobster Meat	Boiled	0.25	166	0.25	0.25
	Tail and Claw	0.50	166		
Soft Shell Clams	Shucked	0.5	119	1.5	0.5
		1.5	119		

In addition to studies on fresh fish, experiments were conducted on precooked codfish prepared by frying, boiling in corn syrup, boiling in tomato juice, and blanching. The results indicated that irradiation of these cooked products, between 0.25 and 1.5 megarad, provided storage life up to 3 to 4 months at 35° F.. Cooking in corn syrup or tomato juice seemed to offer no protection against quality losses due to irradiation.

The Seattle Laboratory of the Fish and Wildlife Service⁷, has conducted considerable experimentation on Pacific cod fillets as well as a survey of irradiation effects on other commercially-processed marine products. Cod fillets packed in C-enamel cans or in mylar polyethylene pouches were held in wet ice or at 35° F. prior to and after irradiation at doses of 0.75 to 1.5 megarad. The products were first evaluated 9 days after packing (5 days after irradiation); they were prepared by baking (350° F.), pan frying (500° F.) and deep-fat frying (375° F.). In addition to sensory and bacterial examinations, chemical analyses of total volatile base and total volatile acid were performed periodically during storage. Significant results are summarized in Tables 2-5 and 2-6.

Initially, all samples of Pacific cod fillet had a slightly scorched odor and flavor. Those receiving less than 1.0 megarad had acceptable odor and flavor. There were no detectable differences in appearance among the various samples. In general, the irradiated samples lacked typical fresh fish flavor. At 0.75 megarad storage life was increased to 16 weeks in wet ice; however, the samples darkened and became tough. All had a slight, but not objectionable, irradiation odor and flavor. No spoilage flavors were found in any instance during the 16-week storage period.

Screening studies on various smoked and frozen seafoods showed most of them, with the exception of salmon, to be acceptable at doses of 0.75 to 1.0 megarad. For raw silver, salmon steaks, the maximum acceptable dose appeared to be 0.5 megarad, although storage life at 40° F. appeared to be quite limited. The results are summarized in Table 2-7.

Surveys were made at the College Park Laboratories on the effects of irradiation from 0.01 to 6.0 megarad on shell fish and shell fish products. These were packaged in evacuated Cryovac bags and held in wet or dry ice prior to and after irradiation.

Packaged raw shrimp was considered unacceptable at any irradiation dose. Packaged crab was acceptable after 60-days' storage at 35° F., despite a stringy texture and bitter flavor. Packaged,

TABLE 2-5. Quality Evaluation by Chemical & Organoleptic Tests on Irradiated Precooked Cod Fillets Storage Intervals at Refrigeration Temperatures

History of Samples		Quality Evaluation			
		Organoleptic Examination (1)	Total Volatile Base (2) Mg. N/100 g.	Total Volatile Acid No. (3)	Total Plate Counts (4) Bacteria/
Unirradiated controls 0 megarad	Iced 4 da(5)	good	6.3	8.7	(1) 710,000 (2) 220,000 (3) 770,000
	Iced 3 weeks	poor	60.4	109.8	--
	Iced 4 weeks	very poor	69.8	132.3	--
	Iced 4 da(5)	good	8.4	8.4	(1) 150 (2) 110
Irradiated 0.23 mega-rad	Iced 4 weeks	fair	8.8	10.9	--
	Iced 6 weeks	fair	21.8	29.2	--
	Iced 8 weeks	fair	42.2	87.5	(1) 380x10 ⁶ (2) 410x10 ⁶
Irradiated 0.70 mega-rad	Iced 4 da(5)	reasonably good	10.5	8.0	10
	Iced 4 weeks	fair	15.8	9.9	--
	Iced 6 weeks	fair	*	*	--
	Iced 8 weeks	fair	*	*	(1) 120x10 ⁶ (2) 140x10 ⁶
	Iced 16 wks	fair	*	*	--
	Iced 20 weeks	poor	--	--	--
Irradiated 0.46 mega-rad	Iced 4 da(5)	reasonably good	--	--	20
	8 wks at 40° F	fair	16.2	11.4	(1) 1.0x10 ⁶ (2) 1.4x10 ⁶
	14 wks at 40° F	poor	*	*	(1) 1,000 (2) 1,000 (3) 1,000 (4) 1,000

(1) Good: normal or original quality w/non-presence of quality defect; reasonably good; trace of slight quality defect - not objectionable; fair: moderate presence of quality defect; poor: on borderline edibility; very poor: inedible.

(2) Analyses made by Food, Chem. & Res. Labs., using method of Stansby et al; Ind. & Eng. Chem., Anal. vol. 16, p. 593 (1944)

(3) Analyses made by Food, Chem. & Res. Labs., using procedure of "Methods of Anal.", A.O.A.C., 7th ed. pp. 297-300 (1950).

(4) Analyses made by Food, Chem. & Res. Labs., using tryptone glucose yeast extract agar; plates were incubated at 30° C. for 5 days.

(5) Four days were required for shipments to and from MTR, Idaho Falls, Idaho, for irradiation of samples.

*Analysis not completed.

Chemical & Organoleptic Tests on Irradiated Precooked Cod Fillets After Various
Incubation Temperatures

Organoleptic Examination (1)	Quality Evaluation		
	Total Volatile Base (2) Mg. N/100 g.	Total Volatile Acid No. (3)	Total Plate Counts (4) Bacteria/g.
Good	6.3	8.7	(1) 710,000 (2) 220,000 (3) 770,000
Poor	60.4	109.8	--
Very poor	69.8	132.3	--
Good	8.4	8.4	(1) 150 (2) 110
Fair	8.8	10.9	--
Fair	21.8	29.2	--
Fair	42.2	87.5	(1) 380x10 ⁶ (2) 410x10 ⁶
Reasonably good	10.5	8.0	10
Fair	15.8	9.9	--
Fair	*	*	--
Fair	*	*	(1) 120x10 ⁶ (2) 140x10 ⁶
Fair	*	*	--
Poor	--	--	--
Reasonably good	--	--	20
Fair	16.2	11.4	(1) 1.0x10 ⁶ (2) 1.4x10 ⁶
Poor	*	*	(1) 1,000 (2) 1,000 (3) 1,000 (4) 1,000

W/non-presence of quality defect; reasonably good; trace of slight presence
Fair: moderate presence of quality defect; poor: on borderline of

s. Labs., using method of Stansby et al; Ind. & Eng. Chem., Anal. Ed.,
s. Labs., using procedure of "Methods of Anal.", A.O.A.C., 7th Ed.,
s. Labs., using tryptone glucose yeast extract agar; plates were incubated
at 37°C for 24 hours at and from MTR, Idaho Falls, Idaho, for irradiation of samples.



Table 2-6. Quality Evaluation by Chemical & Organoleptic Tests on Irradiated Cod Fillets After Various Intervals at Refrigerated Temperatures

History of Sample		Organoleptic Examination (1)	Quality Evaluation		
			Total Volatile Base (2) Mg. N/100 g.	Total Volatile Acid No. (3)	Trimethylamine (4) Mg. N/100 g.
Unirradiated controls, 0 megarad, packed in cans	Iced 4 da (6)	good	8.0	8.9	0.14
	Iced 4 da + 6 day at 35° F	reasonably good; mod. sweet odor	46.8	66.5	6.4
	Iced 4 days + 10 days at 35° F	very poor; spoilage odors; off flavors	64.0	110.0	11.4
	Iced 4 da + 14 days at 35° F	very poor	69.9	145.6	16.6
	Iced 4 da (6)	reasonably good	6.6	6.2	0.16
	Iced 4 days + 3 weeks at 35° F	reasonably good	33.8	47.1	4.4
Irradiated at 0.1 M/rad packed in cans	Iced 4 days + 6 weeks at 35° F	fair	22.5	34.4	1.2
	Iced 4 days + 9 weeks at 35° F	very poor	23.9	74.6	1.4
	Iced 4 days + 12 wks at 35° F	very poor	68.2	174.0	2.1
	Iced 4 days (6)	reasonably good	9.3	6.4	0.21
	Iced 4 days + 3 wks at 35° F	reasonably good	15.9	11.6	0.26
	Iced 4 da + 6 wks at 35° F	fair	31.8	13.8	0.48
Irradiated at 0.2 M/rad packed in cans	Iced 4 da + 9 wks at 35° F	fair to poor	21.4	14.4	0.80
	Iced 4 da + 12 wks at 35° F	very poor	24.7	24.4	0.80

(1) Good: normal or original quality with non-presence of quality defect; reasonably good: trace or quality defect - not objectionable; fair: moderate presence of quality defect; poor: on borderline of very poor: inedible.

(2) Analyses made by Food, Chem. & Res. Labs., using method of Stansby et al.; Ind. & Eng. Chem., Anal. p. 593 (1944).

(3) Analyses made by Food, Chem. & Res. Labs., using procedure of "Methods of Anal.", A.O.A.C., 7th Ed (1950).

(4) Analyses made by Food, Chem. & Res. Labs., using procedure of W.J. Dyer, J. Fish Res. Bd. Can. 6, 1358 (1945).

(5) Analyses made by Food, Chem. & Res. Labs., using tryptone glucose yeast extract agar; plates were for 5 days. Each value represents an average of analysis in duplicate per can.

(6) Four days were required for shipments to and from MTR, Idaho Falls, Idaho, for irradiation of samp

al & Organoleptic Tests on Irradiated Cod Fillets After Various Storage
 mperatures

rganoleptic xamination (1)	Quality Evaluation			
	Total Volatile Base (2)	Total Volatile Acid No. (3)	Trimethyl- amine (4)	Total Plate Counts (5)
	Mg. N/100 g.		Mg. N/100 g.	Bacteria/g.
ood	8.0	8.9	0.14	0.5 x 10 ⁶
easonably good;				(1) 1.3 x 10 ⁶
od. sweet odor	46.8	66.5	6.4	(2) 0.5 x 10 ⁶
ery poor; spoil-				(1) 5.9 x 10 ⁶
ge odors; off				(2) 5.9 x 10 ⁷
lavors	64.0	110.0	11.4	(3) 4.3 x 10 ⁶
				(1) 5.4 x 10 ⁶
ery poor	69.9	145.6	16.6	(2) 1.4 x 10 ⁷
				(3) 1.2 x 10 ⁷
easonably good	6.6	6.2	0.16	4.2 x 10 ⁴
				(1) 2.7 x 10 ⁷
easonably good	33.8	47.1	4.4	(2) 5.0 x 10 ⁶
				(3) 5.6 x 10 ⁶
				(1) 0.7 x 10 ⁶
air	22.5	34.4	1.2	(2) 4.7 x 10 ⁸
				(3) 3.2 x 10 ⁸
				(1) 4.6 x 10 ⁸
ery poor	23.9	74.6	1.4	(2) 4.3 x 10 ⁸
				(3) 2.1 x 10 ⁸
ery poor	68.2	174.0	2.1	--
easonably good	9.3	6.4	0.21	950
				(1) 800
easonably good	15.9	11.6	0.26	(2) 140,000
				(3) 5,400
				(1) 3.7 x 10 ⁵
air	31.8	13.8	0.48	(2) 1.6 x 10 ⁵
				(3) 0.3 x 10 ⁵
				(1) 1.3 x 10 ⁶
air to poor	21.4	14.4	0.80	(2) 0.8 x 10 ⁶
				(1) 1.3 x 10 ⁷
ery poor	24.7	24.4	0.80	(2) 6.2 x 10 ⁷

with non-presence of quality defect; reasonably good: trace or slight presence of
 r: moderate presence of quality defect; poor: on borderline of edibility;

. Labs., using method of Stansby et al.; Ind. & Eng. Chem., Anal. Ed., Vol. 16,

. Labs., using procedure of "Methods of Anal.", A.O.A.C., 7th Ed., pp. 297 - 300

. Labs., using procedure of W.J. Dyer, J. Fish Res. Bd. Can. 6, No. 5, pp. 351 -

. Labs., using tryptone glucose yeast extract agar; plates were incubated at 30° C.
 verage of analysis in duplicate per can.

ents to and from MFR, Idaho Falls, Idaho, for irradiation of samples.



TABLE 2-7. Summary of Work Conducted at the Fishery Technology Laboratory, Seattle, Washington

<u>Species</u>	<u>Treatment</u>	<u>Maximum Dose for Acceptance</u>
Clams (Minced Razor)	Heat Processed	1.0 Megarad
Kippered Cod	Steamed	1.5
	Frozen	1.0
Smoked Oysters	Heat Processed	1.0
Crabmeat	Frozen	0.75
Alaska Shrimp	Frozen 1 year	0.75
Oregon Shrimp	Fresh	0.25
Kippered Black Cod	Frozen	1.5
Kippered Salmon	Frozen	0.75
Kippered Sturgeon	Frozen	0.75
Kippered Tuna	Frozen	0.75
Washington Shrimp	Frozen Commercial	0.25
Petrale Sole	Filletts Frozen	0.75
Halibut	Frozen, cans	0.75
Silver Salmon	Frozen Steaks Under Vacuum	0.5
Salmon Steaks	Precooked Breaded	0.75

cooked picked crabmeat, and breaded frozen and precooked shrimp were acceptable at 0.75 megarad; packaged breaded frozen and precooked oysters withstood 0.5 megarad at doses above 0.25 megarad, and 35° F. storage. Bacterial counts were essentially negative.

From results obtained in its studies, the College Park Laboratory concluded, "The irradiated products packaged in Cryovac bags and stored at normal refrigerated temperatures showed some extension of storage life, but this was obtained at the expense of changes in the normal flavor and texture of the various products. Packaged crab meat was the only product for which the flavor and texture were not affected by enzymatic or bacterial spoilage, or by irradiation."

Other studies directed toward determining microbiological aspects of irradiated marine products have provided valuable information, including:

Codfish portions which were either deep-fat-fried or boiled in tomato juice before irradiation to 230,000 rad were stored at 35° F. without mold for 112 days and 118 days, respectively. In another experiment, Pacific cod fillets canned raw were stored for 5 weeks at melting ice temperature after irradiation to 0, 70,000, 140,000, 230,000 and 460,000 rad. Bacterial counts were made weekly. The unirradiated control counts reached the level of 10^6 organisms per gram in 1 week; the 70,000 and 140,000 rad samples in 2 weeks; and the 230,000 rad samples in 5 weeks. At this time the 460,000 rad samples still showed only 10^3 per gram. It was also noted in this study, as mentioned earlier in the discussion on meats, that the normal spoilage organisms, Pseudomonas and Achromobacter, appeared to be destroyed by the radiation, leaving Micrococci and Flavobacterium predominant. This finding may explain why typical bacterial spoilage does not occur. It also indicates that this method of preservation has some promise⁶.

Coliform counts and tests for coagulase-positive staphylococci were negative in cooked crab cakes and raw headless shrimp in the shell after a 1 million rad dose. However, raw shrimp which had been peeled and deveined showed a coliform MPN of 800 per ml. The standard plate count of these samples varied with processing conditions. The results of storage tests are not complete and final comment must be reserved⁷. Psychrophilic counts made on raw and blanched pollack, cod and butterfish after 49, 53 and 50 days, respectively, at 35° F. showed counts of less than 1000 organisms per gram on all samples irradiated to 230,000 rad⁸. Pre-cooked Breaded Fish Sticks irradiated to 250,000, 500,000 and 1 million rad before storing at 35° F. and room temperature, showed for some doses a different type of spoilage

for canned samples than that for samples packed in plastic pouches. Samples given the lowest dose in plastic became sour after 8 weeks; those in cans stored 12 weeks were musty. At the highest dose, counts remained less than 10 per gram for 12 weeks at 35° F. and for 14 weeks at room temperature, regardless of packaging. At the refrigerator temperature, samples receiving a dose of 250,000 rad showed an initial SPC of 250 per gram which increased to 920,000 per gram in 14 weeks. Non-irradiated samples had a shelf-life of less than 4 weeks at 35° F.; the counts reaching 180 million in this time⁷.

It should be re-emphasized that increases in the storage period at refrigerated temperatures, especially for marine products, should be approached with utmost caution in view of the knowledge that Cl. botulinum Type E organisms have been most closely associated with marine products¹¹.

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CHAPTER 3

RADIATION PRESERVATION OF VEGETABLES

The primary purpose of low-dose radiation of fresh vegetables is to increase storage life and thereby extend their holding time and market life. This preservation process reduces surface microbiological flora and inhibits the progress of post-harvest diseases. Used in conjunction with controlled temperature and humidity, this process offers a means of extending the holding time substantially. Threshold levels have been established to assure that vegetables retain their desirable texture, odor, flavor, and appearance. Here, as in conventional processing, accurate and reliable measuring devices are essential, and are under development.

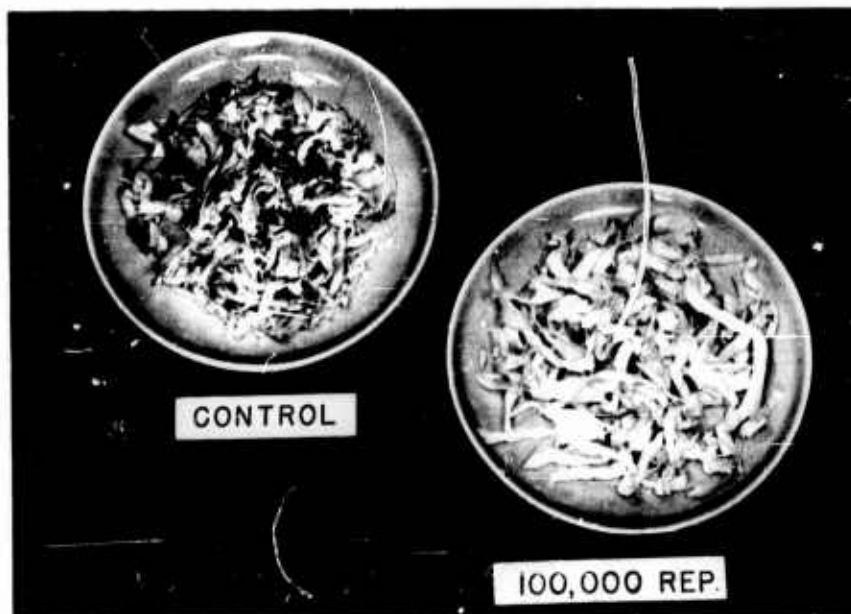


Figure 3-1. Coleslaw, cellophane-packaged, and processed with low-dose radiation, remained fresh for 35 to 40 days. Unirradiated slaw spoiled in 7 to 8 days. Both samples were stored under normal refrigerated temperatures.

Low-level radiation processing may also be used to extend the refrigerated shelf life of blanched vegetables. When properly packaged, and kept at normal refrigerated temperatures after "pasteurization" blanched vegetables could be distributed by the retail trade in much the same manner as "pasteurized" milk.

Low-level irradiated foods could substantially reduce the current freezer-refrigerated storage requirements for frozen foods, inasmuch as irradiated foods may be retained under normal refrigerated storage.

Microbiological studies on the radiation stabilization of fresh vegetables have had two objectives, (1) inhibition of sprouting in the case of onions and potatoes, and (2) control of plant pathogens, such as fungi and bacteria in all vegetables.

Data accumulated under intensive studies on the response of vegetables irradiated at low dosages indicated that of the seventeen vegetables of commercial interest, four were benefited; some showed moderate improvement in keeping qualities; and others appeared to be damaged.

Detailed data on each of the vegetables are presented on the following pages.

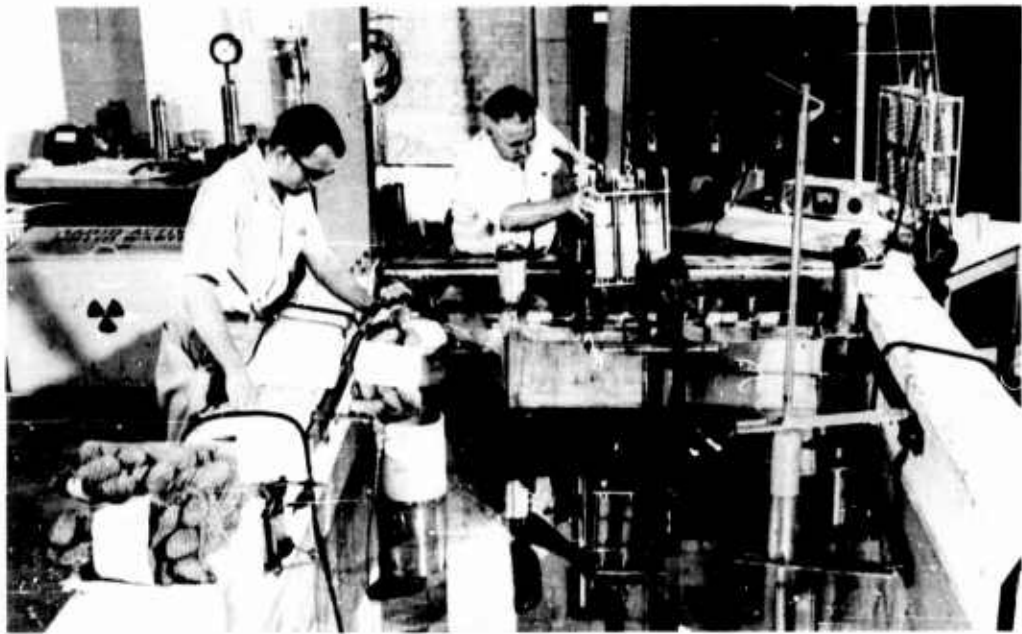


Figure 3-2. Potato irradiation, Materials Testing Reactor, Idaho Falls, Idaho

1. RADIATION PRESERVATION OF POTATOES

Research findings⁹ some ten years ago indicated that low doses of irradiation inhibited sprouting in potatoes. Since that time a great deal of research has been directed toward exploiting this long-sought discovery. Investigations have encompassed such areas as the effects of irradiation processing on rot; quality and acceptance; weight loss and moisture content; ascorbic acid content; sprouting; suberization; total reducing, and non-reducing sugar content; effect of different curing schedules; and storage temperatures. Findings have been most rewarding.

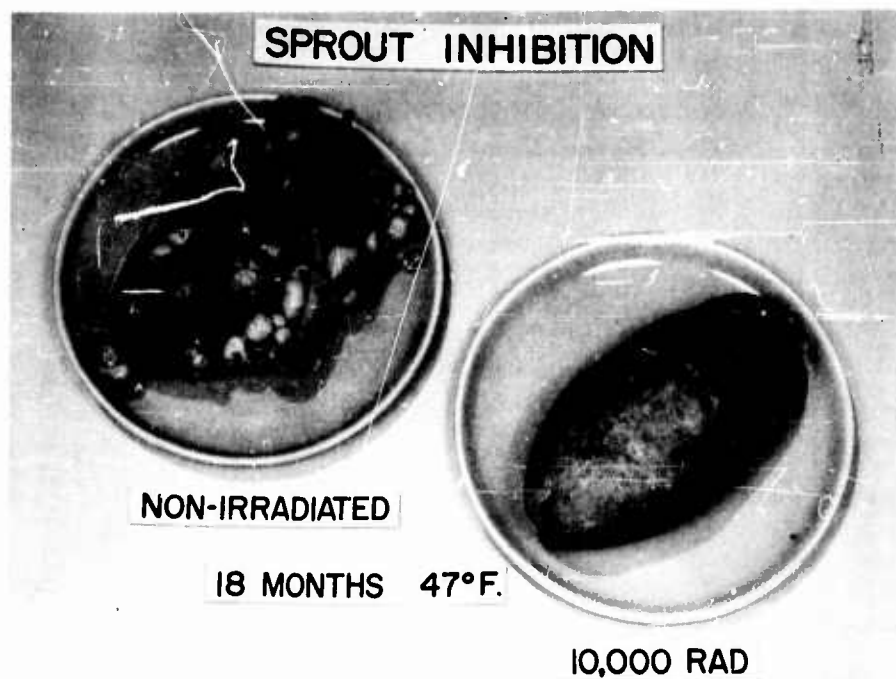


Figure 3-3. Low-dose irradiation prevents potatoes from sprouting during extended periods of storage.

Some tests have shown that an increase in sugar content occurs at storage temperatures of 30° to 40° F., but does not become excessive when the storage temperature is raised to 50° F., and above. However, sprouting and rot increase at the higher temperatures. The objective is to achieve

optimum storage temperatures, with a treatment that inhibits sprouting and dehydration.

The significant results of research efforts directed toward developing low-dose irradiation processes for the preservation of potatoes, include:

The Effects of Radiation on Sprouting

According to experiments on varietal response, conducted at Purdue University⁴, sprouting of White Sebago, Katahdin, and Russet Burbank potatoes stored at 41° F. was prevented by exposure to 5,000 rad of gamma radiation, the lowest dosage used at 41° F. Red Pontiac potatoes stored at 41° F. required 7,500 rad to inhibit sprouting.

University of Michigan studies² showed that control potatoes had sprouts from two to six inches long after being stored at 45° and 40° F. for about 5 months. None of the stored potatoes irradiated above 5,000 rad sprouted. Potatoes receiving 5,000 rad and stored at 45° F. developed a few very short sprouts (3-5 mm long), much shorter than those of the control potatoes, stored at the same temperature.

In storage tests conducted at the University of Maine⁵, all the control samples sprouted, but sprouting of the irradiated samples was inhibited, with a few exceptions.

Purdue University⁴ reported that at 47° F. storage 7,500 rad prevented sprouting on all 4 varieties of potatoes used in their experiments (White Sebago, Katahdin, Russet Burbank and Red Pontiac).

In experiments conducted at Cornell University⁸ on potato varieties, including Katahdin, Green Mountain, Kennebec and Russet Burbank, the potatoes were irradiated shortly after harvest in the gamma field at Brookhaven at dosages of 5,000; 7,500; 10,000; 12,500; and 15,000 rad, and stored in 50° F. storage. Irradiated samples were compared with unirradiated potatoes which were used as control samples. Relatively complete sprout control with all varieties was obtained with 15,000 rad. Commercial sprout control was obtained with Katahdin at 7,500 rad, Green Mountain at 10,000 rad, Kennebec at 12,500 rad and Russet Burbank at 15,000 rad.

Purdue University⁴ reported that at 55° F. storage, 7,500 rad prevented sprouting on White Sebago, Katahdin, and Russet Burbank; Red Pontiac varieties required 12,500 rad for complete inhibition of sprouts, although sprouting was practically inhibited by 10,000 rad.

Effect of Radiation on Respiration

In tests conducted at the University of Michigan² on whole tubers irradiated at 0, 5,000, 15,000, 25,000, 100,000, and 200,000 rad, it was reported that with the exception of the tubers that received 5,000 rad, there was a considerable increase in respiration two days after irradiation. In general, observations indicated that after the first rise, the rate of respiration coincided with the dosage given. For example, those given the lowest dosage respired the least, and those having received the highest dosage (200,000 rad) respired the most.

In tests conducted by AMF Atomics, Inc³, it was reported that respiration of potatoes used as control items increased with sprouting and spoilage. Respiration increase of irradiated samples at the end of the study was possibly due to the presence of rot on some test samples.

The Effect of Radiation Upon the Reducing, Non-Reducing, and Total Sugar Content of Potatoes

Investigators at the University of Maine⁵ reported that storage temperature greatly influenced the amounts of reducing sugars in all potato samples (Maine Katahdin, Maine Russet Burbank, Idaho) throughout the storage period. During the colder months, there was an increase in reducing sugars, whereas sharp decreases occurred during the summer months. Likewise studies at the University of Michigan² indicated that the lowest temperature level results in elevated sucrose and reducing sugar contents, for both irradiated and non-irradiated Russet and Sebago varieties, but all other storage temperatures resulted in low sugar levels.

None of the varieties under test at the University of Maine⁵ exhibited any established trend in content of reducing sugars, as to high versus low irradiation dosage. With a few exceptions, the values for both dosages were very similar. It appeared, however, that the content of non-reducing sugars increased in proportion to dose levels.

Storage temperatures appeared to have a much greater effect on total sugar content for all three varieties than either of the irradiation treatments.

The University of Michigan² reported that the effect of radiation dosage on the reducing sugar and sucrose contents of both Russet Rural and Sebago variety potatoes measured directly after irradiation was negligible. Sucrose levels in both Russets and Sebagos following the first storage period, however, showed a marked effect of radiation dosage level. Increasing the dosage level up to 200 kilorad, increased the sucrose level in Sebagos from 0.43 to 3.8% and in Russets from 0.28 to 2.98%. There appeared to be

no consistent effect of radiation up to 50,000 rad on either sucrose or reducing sugar, but there did appear to be an effect on the total. The sum of the two sugars increased slightly with dosage of radiation up to 25,000 rad, and then decreased slightly. When expressed on a dry-weight basis, all doses of radiation appeared to increase the sum of reducing sugar and sucrose by an equal amount.

An effect of increasing doses of radiation on the reducing-sugar level became apparent in both varieties after prolonged storage of 30-34 weeks.

Effect of Radiation on Suberization

In tests conducted at Michigan State University⁶ it was observed that irradiation slightly reduced the speed and extent of suberization, and markedly reduced periderm formation. Irradiation prior to wounding caused greater response as evidenced by periderm inhibition than irradiation after wounding. Periderm formation in particular was progressively inhibited by increasing irradiation dosage from 2,500 to 15,000 rad.

Cornell University⁸ reported that Katahdin tubers irradiated with 12,500 rad in the gamma field at Brookhaven, and check tubers, were held for 10 months at 50° F. and a relative humidity of 85%. To determine wound periderm activity a strip of tuber surface was peeled at uniform depth and the peeled area allowed to heal at 70° F. and 85% relative humidity. Ten observations were made on each tuber sample.

In the first experiment observations were made 4, 8, and 10 days from peeling. The results of this experiment are shown in the following table:

TABLE 3 - 1. Potato Wound Periderm Activity 10 Months After Irradiation

	Days from Wounding	Depth in Microns Suberized Layer	No. of Cells in Wound Periderm
12,500 Rad	4	212	3.5
Control	4	233	3.4
12,500 Rad	8	261	5.6
Control	8	379	7.6
12,500 Rad	10	223	5.0
Control	10	424	9.0

In a second experiment using similar material, observations were made 10 days from peeling for suberization. Observations were also made on normal periderm formation. Four hundred observations were made for each of the averages given in the following table:

TABLE 3 - 2. Suberization of Potatoes

Dosage	Wound Periderm		Normal Periderm	
	Depth in Microns of Suberized Layer	No. of Cells in Wound Periderm	Depth in Microns of Suberized Layer	No. of Cells in Wound Periderm
12,500 Rad	319	5.3	126	7.4
Check	318	5.8	146	8.7

The Effects of Radiation on Quality and Acceptance

In potato tests at various temperatures⁴, shrivelling was observed, generally, to be directly related to sprouting. Hence, at 41° F. where sprout growth on the controls was retarded there was little difference in appearance between White Sebago, Katahdin, and Russet Burbank controls and corresponding irradiated potatoes up to one year. After one and a half years at 41° F., however, varietal differences were evident. Unirradiated Red Pontiac potatoes sprouted rapidly at 41° F., and were badly shrivelled, whereas the non-sprouted irradiated potatoes had an excellent appearance.

After one year's storage a grey discoloration within the vascular ring developed in Katahdin potatoes stored at 41° F. and 47° F., and was more prevalent and severe after one and a half years. This discoloration appeared not to be restricted to any one treatment; but it was not observed in potatoes stored at 55° F.

Red Pontiac potatoes still remaining at 47° F. storage after one and a half years showed considerable internal breakdown. The breakdown area was firm but had a nauseating odor, not observed at 41° and 55° F. The breakdown was not restricted to any one treatment. Russet Burbank potatoes did not develop any internal disorders. White Sebago greyed slightly, but the principal objection to this variety was the rapid weight loss and shrivelling.

After one year's storage, potatoes were sectioned, knife-peeled, and observed for rate of raw darkening. At this time the shrivelled control potatoes darkened rapidly and severely, whereas the more turgid irradiated potatoes darkened slowly, with less severity. After a year and a half in 41° and 47° F. storage, the rate of darkening following mechanical abrasive

peeling seemed, as before, to be inversely proportional to the turgidity of the tubers; controls generally darkened more rapidly and severely than their irradiated counterparts.

This finding was not corroborated by other investigators⁸, who reported that, in general, peeled-darkening was increased by radiation in all potato varieties used.

In a 1956 experiment, Dallyn and Sawyer⁸, reported an increase in after-cooking blackening of Katahdin tubers irradiated to 40,000 and 80,000 rad gamma and fast electron irradiation. This phenomenon was more pronounced with gamma radiation. In a later experiment, however, both gamma and fast-electron radiation increased the after-cooking darkening of all varieties tested at the dosage necessary for commercial sprout control.

In limited cooking tests⁴, it was reported that of the four varieties tested at one year, and at a year and a half, Russet Burbank was the most acceptable. However, at the latter period this variety had a slightly dark and translucent appearance as well as a mildly sweet flavor following boiling. After two years these potatoes did not cook well. After boiling or baking the potato flesh was very dark and translucent, with a sticky texture and sweet flavor.

In storage tests conducted at Rogers Bros. Seed Company¹⁰, dehydrated potato flakes made from both control and irradiated potatoes showed no significant differences in flavor, texture, odor, color, or Vitamin C content when reconstituted into mashed potatoes.

When diced dehydrated potatoes were made from irradiated and control tubers, no significant differences were noted in rehydration. Diced potatoes formed from irradiated potatoes were significantly darker in color than control samples, however, making them unsatisfactory for commercial use.

Effect of Radiation on Weight Loss and Moisture Content

Investigators at the University of Michigan² determined weight loss of Idaho potatoes as a function of radiation dosage, storage temperature, storage humidity and storage time. Increases in the storage temperature of irradiated potatoes resulted in increases in weight loss with time, whereas increases in the storage temperature of the control potatoes resulted in an increased rate of weight loss, probably because of the higher metabolic rate and greater surface for transpiration presented by the sprouts. Potatoes receiving increasing doses of radiation, but held at one storage temperature, showed a marked decrease in weight loss with increase in radiation dose up to 15,000 rad. Radiation doses of 50,000 rad and higher resulted in the same weight loss for the same storage conditions. It appeared that 15,000 rad was essentially as effective as higher doses in checking weight loss.

In storage tests at different humidities, the potatoes lost weight in inverse ratio to the air humidity. It was also observed that irradiated potatoes lost less weight than non-irradiated controls at the same relative humidity.

In work completed at Purdue University⁴ it was reported that at 41° F. the rate of weight loss of White Sebago, Katahdin, and Russet Burbank control and irradiated potatoes was very similar, up to around 300 to 345 days after harvest. However, this was true of the control and irradiated Red Pontiac potatoes up to only 220 days after harvest. Beyond these time periods, sprouting increased the rate of weight loss of the controls. With any one variety only slight differences in the rate of weight loss existed between the five irradiation dosages: 5.0, 7.5, 10.0, 12.5 and 15.0 kilorad.

At 41° F., the only striking difference in the rate of weight loss between curing schedules was shown by the variety, White Sebago. Differences in rate of weight loss between curing schedules in the case of the other varieties were slight.

At the end of 440 days, striking differences in the rate of weight loss existed between irradiated potatoes of the four varieties studied.

At 55° F., no marked differences in rate of weight loss existed between the different curing schedules. Differences in the rate of weight loss at 55° F. between varieties was also very marked after a 280-day storage period.

Potatoes which were irradiated at various time intervals after harvest were stored at 47° F. only. Rate of weight loss was not altered by irradiation date.

Differences in the rate of weight loss between varieties again was marked. In 400 days at 47° F., irradiated potatoes of the White Sebago variety lost about 21%, Katahdin lost 16%, Red Pontiac lost 15%, and Russet Burbank lost 11%.

Effect of Radiation on Ascorbic Acid Content

Results of tests⁸ on three varieties of tubers (Pontiac, Ontario, Green Mountain) radiated at four dosages (varying up to 60,000 rad) in the gamma field at Brookhaven, indicated a decrease in ascorbic acid as the dosage increased, with all varieties.

Investigators attempted to develop a correlation coefficient between black spot index and ascorbic acid content. They observed a highly significant

negative correlation when considering all treatments together; however, when figures for the control and irradiated treatments were separated, the entire effect lay within the irradiated portion of the experiment.

When potato tubers were removed from lower temperatures⁵ an apparent increase in total and reduced ascorbic acid content resulted. There occurred an initial loss (more drastic for the irradiated than the controls) which was arrested after four months' storage; and then, an apparent synthesis of ascorbic acid continued in both treated and untreated tubers until approximately the eighth or ninth month of storage. This period of synthesis was followed by another decrease, which was, for all potatoes, much greater in the control samples than in the irradiated lots.

The Effect of Radiation on Rot

Storage rot of potato tubers exposed to ionizing radiation below 500,000 rad intensity was studied on Sebago tubers exposed to cobalt radiation up to 500,000 rad. There was no evidence that ionizing radiation either reduced incidence of rot, or enhanced effectiveness of normal defense reactions in the tuber. Incidence of ring rot developing in naturally-diseased tubers was not modified by ionizing radiation; occasionally ring rot symptoms were masked by high incidence of soft rot following severe irradiation injury.

Incidence of miscellaneous naturally-occurring rots including Fusarium tuber rot and bacterial soft rot in non-inoculated tubers was highest in the high levels of irradiation (500,000 rad), and the rate of rot spread through tuber tissue was increased at the high irradiation intensities. This trend observed at 129 days at 68°-70° F. or in 365 days at 34°-40° F. was similar in wounded non-inoculated controls, and in tissue inoculated either with bacterial soft rot or with Fusarium tuber rot.

These investigators concluded that ionizing radiation influences susceptibility of rot in potato tubers by apparently modifying two different reactions; one was delayed and permanent, from which the tuber did not recover; the second was apparently temporary, and the tuber recovered within a few days. Irradiated tissue was delayed in normal wound healing process resulting in a degree of susceptibility greater than that of nonirradiated control tubers at comparable periods of time. Rot progressed in irradiated samples throughout the storage period at a rate in excess of the nonirradiated controls.

Storage rots of potato tubers exposed to minimum sprout inhibiting levels of ionizing radiation were studied by these same investigators. All tubers used in these tests were portions of the same lots of tubers used for storage tests at Purdue University.

Storage rot incidence of potato tubers following exposure to ionizing irradiation was determined with relatively large lots of tubers at low levels (2.5 to 15.0 kilorad) of intensity.

Nonwounded, non-inoculated tubers developed little storage rot at these levels of irradiation and at the 10-15 kilorad intensities sprouting was inhibited.

TABLE 3 - 3. Incidence of Rot in Non-Inoculated, Non-Infected Potato Tubers Exposed to Low Dosage Radiation

Dose in Megarad	0	2.5	5.0	7.5	10.0	12.5	15.0
<u>Variety</u>							
Russet Burbank	0	8%	20%	18%	1%	5%	12%
Red Pontiac	50%	25%	1%	5%	10%	2-1/2%	13%
Katahdin	22%	12%	5%	5%	26%	25%	27%
Sebago	15%	14%	14%	13%	24%	22%	28%

Cell membrane permeability was increased by exposure to ionizing radiation.

Recovery from irradiation injury as measured by increased cell membrane permeability occurred within 3 days at irradiation intensities of 45,000 rad and below.

At irradiation levels of 45,000 and 135,000 rad Fusarium sambucinum grew through cells and cell walls of irradiated tissue producing almost parallel hyphae, but at lower levels of radiation intensity its manner of growth was essentially similar to the controls. At low radiation dosages bacterial soft rot developed in a typical manner with cell wall breakdown in the presence of masses of bacterial cells while at high radiation levels soft rot appeared to be less intense, with less abundant bacterial growth and less rapid and complete cell wall breakdown.

In tests conducted at Purdue University⁴ it was shown that decay of potatoes stored at 41° F. was generally light up to around 430-550 days from

harvest depending on the variety. Beyond these times, decay rate increased. Differences in decay rate between controls and respective irradiation treatments were generally minor. Also, no major differences in decay existed between the curing schedules.

As would be expected, decay at 55° F. occurred sooner and advanced more rapidly than at 41° F. In general, extensive decay occurred somewhat later and to a lesser degree in the intermediate dose levels of 7.5 and 10.0 kilorad than in the controls and higher dose levels. Where sprouting was not excessive in the 5.0 kilorad treatments, decay was also less than in the controls or dosages greater than 10.0 kilorad. In the best treatments, decay was not extensive until sometime between 270 and 300 days from harvest. Differences in decay between curing schedules were minor.

Decay developed a little more rapidly at 47° F. in irradiated Katahdin and Russet Burbank potatoes than in corresponding controls. However, decay developed less rapidly in the irradiated White Sebago and Red Pontiac potatoes than in their corresponding controls. These differences did not appear until sometime after 420 days from harvest at which time decay was progressing rapidly in all treatments. The decay rates of the different varieties were similar at all three storage temperatures.

Potatoes naturally infected with bacterial ring rot, irradiated at the University of Michigan, Fission Products Lab.², and stored at 34° F. and 68° F. at Michigan State University, gave no evidence of tuber injury as a result of irradiation 10 days after treatment. By the end of 30 days, majority of the tubers receiving 500,000 rad were rotted and a few receiving 200,000 rad had broken down. Positive diagnosis of ring rot in tubers receiving the 500,000 rad treatment could not be made due to the masking effects of severe radiation injury.

This radiation injury resembled severe freezing injury in many respects. Affected tubers were often somewhat cheesy in consistency, later breaking down into a soft rot. Affected tubers often had a fermented odor and the general appearance was more suggestive of storage rots of the sweet potato rather than that of the Irish potato.

Many tubers held at 68° F. were badly wilted after 80 days in storage. Nonirradiated controls were so badly sprouted at the 129-day inspection level that all tubers were cut for ring rot evaluation. In this evaluation there was some evidence that ring rot was developing more slowly in the irradiated tubers than in the untreated tubers.

It was found that gamma and fast electron irradiation increased the incidence of black spot in potatoes⁸, although the effect of irradiation on black spot varied considerably with variety. The dosage necessary for

commercial sprout inhibition and the dosage at which increased black spot is obtained due to irradiation overlap with most varieties. The Cornell University Report⁸ concluded that irradiation should be used at as low dosages as possible for commercial sprout control.

Microbiological experiments^{1, 7}, using potatoes inoculated with either late-blight fungi (Phytophthora infestans), bacterial soft-rot (Erwinia carotovora), or dry-rot fungi (F. sambucinum), have shown that the late blight infections appeared to be inhibited for 15 days at 60° - 70° F. by dose levels above 50,000 rad.

Development of Fusarium rot at dosages as high as 500,000 rad indicated that gamma irradiation (a) did not control Fusarium naturally harbored on the surface of the susceptible and/or (b) pre-disposed potatoes to infection by Fusarium. Results of the tuber pack inoculated with bacterial soft-rot were not consistent. In one set of experiments, control of the infection was attained at 45,000 rad, but in another no inhibition resulted at 100,000 rad. Killing was noted in one instance at 135,000 rad. These discrepancies may have been due to inadequate control of the spore inoculum concentration.

In plate cultures, the lowest dosage tested, 25,000 rad, prevented further growth of 24-hour old cultures of P. infestans¹.

For E. carotovora, in no instance did colonies develop following irradiation at 135,000 rad. Colony development was generally precluded at 45,000 rad, except where bacterial suspensions were heavy. Although there was some evidence of inhibition at the 15,000 rad level, the effect was marginal⁷.

Highly pathogenic strains of Fusarium spp. resembling Fusarium sambucinum f6 in culture were isolated with relatively high frequency from irradiated, naturally-infected tubers. With the exception of one isolate, these were pathogenic in both non-irradiated and irradiated tuber tissue.

Isolates of fungus species, which were of intermediate or of low pathogenicity on unirradiated tissue, were relatively invasive in irradiated tissue.

Although irradiated tuber tissue may have been more susceptible than nonirradiated tissue, at least some degree of pathogenicity was required to establish infection.

The incidence of rot in wounded, inoculated tubers was directly proportional to the radiation intensity. However, at low levels of irradiation (below 15,000 rad), the rate of rot progression through tuber tissue could not be correlated with radiation intensity.

A similar but less distinct trend was obtained with E. carotovora⁷.

Rot following inoculation with F. sambucinum f6 was consistently more severe when inoculation followed irradiation than when inoculation preceded irradiation.

Indiana-grown Sebago tubers consistently developed more rot when wounded, or wounded and inoculated after irradiation, than when wounded before irradiation. With the other tuber lots there was no consistent relationship between rot incidence and time of wounding⁷.

Investigation of sweet potatoes inoculated with Rhizopus showed that 100,000 rad gave no control, while 500,000 rad partially decreased the amount of infection but caused injury to the tissue¹.

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2. RADIATION PRESERVATION OF ONIONS

Unlike potato sprouts which start from tissue very close to the surface, the onion shoot or sprout arises from the meristematic tissue deep within the center of the bulb. To inactivate this deeply-imbedded tissue, and achieve the desired sprout inhibition in onions, both gamma and electron radiation have been investigated.

Results of early experiments indicated that to be effective, electron radiation must be directed toward the base of the bulb. Special studies have been conducted to determine the effectiveness of low-dose ionizing energy to inhibit onion sprouting, and significant findings are reported as follows:

Sprouting and Rotting

When Iowa 44 (yellow globe storage type) onion bulbs were treated with 2,500 to 64,000 rad electron irradiation directed to the base of the onion, sprout growth was checked. When it was directed to the top there was no retarding action; on the contrary, sprouting increased at the two highest dosages². No tissue darkening occurred where only the tops or sides of the bulbs were exposed to the beam, and no effect of the treatment on incidence of storage rot was noted.

Basic Vegetable Products, Inc.³ determined that to inhibit external sprouting completely, electron dosages of 500,000 rad at 8-Mev were needed. The internal sprouts of basally-irradiated bulbs were yellow and stunted, though in general these symptoms were not as severe as those caused by gamma irradiations. The least internal sprouting was found in the group irradiated to 500,000 rad at 8-Mev. However, in both external and internal sprouts, the treated samples showed as much or more sprouting than the control samples.

A dosage of 128,000 rad caused noticeable damage to the scales of the onions, and there was some evidence that 64,000 rad was also somewhat injurious. Injured bulbs suffered deterioration of scale color, and increased moisture loss². Tests conducted³ with a linear accelerator showed that the concentrated irradiation caused a significant increase in the optical index. The 500,000 rad level resulted in a higher optical index than the 150,000 rad, and the 8-Mev was higher than the 4-Mev.

Gamma irradiation tests were conducted at Cornell University² from 1955 to 1957, and significant findings include:

- a. Gamma irradiation at dosages of 8,000 or 12,000 rad consistently controlled external sprouting of a number of onion varieties, stored under a wide range of environmental conditions;
- b. Irradiation treatments did not give complete control, but provided a substantial reduction of internal sprouting. Sprouts which appeared were small, yellowish in color, grew very slowly, and seldom extended upwards more than half-way through the bulbs;
- c. A high proportion of irradiated bulbs developed dark growth centers. Apparently the treatments injured the meristematic tissue, causing it to die gradually and turn dark. A very high correlation existed between this disorder and sprout inhibition;
- d. Dosages up through 16,000 rad had no effect on the rotting of onions in storage, or on any other visible external characteristics.

Rooting of Onions in Pre-Packaged Film

Experiments were conducted on pre-packaged onion bulbs² Iowa 44 (yellow globe storage type). In the first experiment bulbs were irradiated in the Brookhaven gamma field with dosages of 4,000, 8,000, 12,000 and 16,000 rad. After irradiation, the onions were left in common storage several weeks and then moved inside to a temperature of 60° F. Four-16 bulb samples of each treatment were later placed in polyethylene bags (16, 1/4 inch perforations) in single layers and kept at a temperature of 60° F. and a relative humidity of 85%.

After six weeks, the onions were examined for sprouting, rooting, amount of rot, external and internal appearance. All irradiation dosages completely inhibited rooting and sprouting under the conditions of this experiment. Long roots appeared on the control samples making them unsuitable for use.

All treated samples were dry and the bulbs were bright in appearance.

No differences were found between treatments in the amount of internal discoloration of the growing-point areas however, as all treatments contained many bulbs with dark, growing-point areas.

In a second experiment, Iowa 44 bulbs removed from 32° F. cold storage and radiated with a Van de Graaff electron generator to dosages ranging from 2,000 to 64,000 rad were then packaged in ventilated film bags, and stored at 60° F. and 80% relative humidity.

When the bulbs were examined for rooting, it appeared that all dosages used effectively controlled rooting when the beam was directed toward the base of the bulb; no treatment was of any value when applied to the top of the bulb. Many of the basally-treated bulbs had discolored internal tissue; however, the appearance of this injury was somewhat different from that produced by gamma irradiation. Sprouts in the controls and top-treated samples were still inside the bulbs, but were green and growing vigorously; those in the basally-treated bulbs were yellow and still very small.

Internal Quality - Flavor, Texture and Color

An experiment was conducted² with bulbs of three varieties, Sweet-Spanish, P. W. 160 (a Sweet-Spanish type hybrid), and Iowa 44, to determine the internal quality, flavor, texture, and color. The first two varieties of onions are large, relatively mild, and are often eaten raw in salads and hamburgers. The other variety is a yellow Globe storage-type onion, moderately pungent, and is used primarily for cooking. The treated bulbs received dosages of 8,000 and 12,000 rad of gamma radiation.

The Sweet-Spanish variety was served raw to a taste panel, the other two varieties were served cooked. In general, irradiation treatments had either negligible or small effects on flavor as determined by the panel. Where differences did exist they were in favor of the treated onions. The Sweet-Spanish onions irradiated with 8,000 rad and tested raw were rated significantly better than onions given the 12,000 rad treatment, or the unirradiated control samples. Iowa 44 onions which had been irradiated with either 8,000 or 12,000 rad were rated better than the control samples. These differences, determined on the cooked product, were highly significant. After an additional two months' storage at 50° F., these differences had evidently disappeared, as it was observed that the treated onions tended to cook lighter than the control samples. The flavor of the P. W. 160 was not affected by treatment.

Results of this study showed that sprouting was inhibited at 8,000 rad and above, and a very slight amount of internal sprouting occurred at this level. Rooting was partially inhibited at 4,000 rad and completely inhibited at 8,000 rad. Rot incidence appeared unaffected by the treatment. Dark growth centers occurred in two out of three experimental conditions at 4,000 rad, and in all cases at 8,000 rad, and above. Control samples did not exhibit this condition.

Chemical Constituents

Interest in what if any effect low-dose radiation might have on the chemical constituents of the onion led to investigations that yielded the following results:

a. Volatiles: No effect of sprout-inhibiting dosages of irradiation on volatile constituents².

b. Solids: No effects of irradiation were indicated on solids^{2,3}.

c. Sugars: No effects on sugar content or volatile constituents were produced by irradiation levels substantially above those required for external sprout inhibition².

Microbiological Aspects

Onions required doses of 200,000 rad to inhibit sprouting and control growth of Botrytis mold in inoculated packs. Control samples showed extensive molding in less than 9 days but samples irradiated to 150,000 and 200,000 rad showed no mold in 14 days at 70° to 75° F., or 30 days at 38° to 41° F.¹.

Injury and Discoloration of the Growing Points

The cause of the growing point discoloration was of concern to many investigators². While the brown growth centers appeared to be bacteriologically sound³, the appearance in a dried product was identical with rot and therefore considered a serious defect. Four different pre-irradiation treatments were tried in order to determine whether time of treatment and/or the condition of maturation of the bulb would affect the degree of darkening. None had any effect on the problem.

It should be emphasized that, normally, the affected area of the onion represented a very small fraction of the entire bulb and its appearance might not be objectionable to many types of users, particularly if the alternative was a sprouted bulb.

Suitability for Dehydration

A relatively small number of samples were analyzed for suitability for dehydration². None of the treatments affected solids content but the higher radiation dosages tended to deteriorate color to some extent, specifically the dark growth centers previously discussed.

It was thought that if the onions could be treated before the growing-point area had enlarged to any great extent, the affected area, which eventually darkened, would be kept to a minimum². Southport White Globe and Sweet Spanish onions were treated at three intervals, 2, 26, and 45 days after harvest with dosages of 0, 4,000 and 8,000 rad gamma radiation. All samples were shipped to California to be tested. Results of this and subsequent tests indicated that the dehydrating quality of irradiated onions had been adversely affected by the development of the dark coloration of the growing points. No other physical or chemical property measured was so affected. Onions have shown no reduction in dehydrating quality at dosages up to 55,000 rad.

Bulk Treatments of Onions with Gamma Irradiation

Inasmuch as, from a commercial point of view, single-layer treatment would not be as desirable as bulk treatment in a suitable container, two varieties of onions, (Iowa 44 and Sweet Spanish) were bagged in 50-pound mesh bags and treated with 0, 4,000, 8,000, 12,000 and 16,000 rad, in an additional experiment.

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3. RADIATION PRESERVATION OF OTHER VEGETABLES

Experimental data indicated that a considerable variation exists regarding the effects of low-dose radiation on fresh vegetables. Lettuce and other leafy vegetables wilted readily; whereas the tough-textured vegetables were benefited. The refrigerated shelf-life of asparagus, peas, snap beans, blanched lima beans, sweet corn, beets, and shredded cabbage was extended from 3 to 6 times by low-dose radiation processing. Dried vegetables, such as navy beans, were also benefited.



Figure 3-4. This photograph shows artificially-infested navy beans 43 days after test inoculations were made. The top picture shows the deteriorated condition of the unirradiated control samples; the bottom picture shows the keeping qualities of beans irradiated at 93,000 rad.

Low-dose radiation research has been conducted on a variety of vegetables, and significant findings include:

Cabbage: Heads of cabbage irradiated at 230,000 rad were acceptable. At 930,000 rad, however, a severe loss of texture and flavor was observed¹⁹.

Shredded Cabbage: Doses of 150,000 to 300,000 rad materially increased the shelf life of shredded cabbage. Radiation products were rated acceptable after 40 days of storage; whereas, the non-irradiated control sample was unacceptable after 7 days¹⁹. Several other experiments on shredded cabbage packed in flexible packets, and stored at 38° F. after irradiation at 50,000; 100,000; 150,000; 200,000 and 300,000 rad, indicated that bad molding in samples receiving doses of 100,000, or less, occurred within 6 weeks. Only a small amount of mold was observed at the three higher doses, and the 300,000 rad level completely inhibited molding for 30 days¹⁴.

Asparagus: According to a study conducted at Utah State University²⁰, the refrigerated shelf-life of hermetically sealed, blanched asparagus was more than doubled by irradiation to 190,000 rad and tripled by irradiation to 370,000 rad. Another investigator¹² found that blanched asparagus irradiated at 930,000 rad and packaged in aluminum foil-mylar was judged to be acceptable and to retain characteristic asparagus flavor after twenty days of storage. Tenderness increased in second-grade blanched asparagus as the irradiation dose advanced. The green color was sustained through twenty days of storage at 40° F. Of much interest was the finding that irradiated asparagus was preferred over the second-grade non-irradiated control. The optimum dose in this study¹⁹ was considered to be 500,000 rad.

In other studies, blanched asparagus spears held in sealed polymylar bags at 50° F. after irradiation to 0, 100,000, 300,000 and 500,000 rad showed molding in the control samples and 100,000 rad dose levels after 12 days, but no mold in samples at the two higher doses after 30 days¹¹.

In another test, blanched asparagus, snap beans, and baby lima beans were irradiated in sealed cans at refrigerated temperatures and stored at 34°-36° F.¹¹ Separate analyses were made for aerobes and anaerobes and as expected the anaerobic counts on the stored samples were higher than the standard plate counts. Findings of storage tests include:

a. Asparagus: Control samples showed an increase in micro-organisms from a Standard Plate Count (SPC) of 300 and an Anaerobic Count (AC) of 450 per gram initially to 900,000 and 2 million per gram, respectively, after 34 days. Samples given 190,000 rad showed an SPC of 90,000 per gram and an AC of 220,000 per gram after 177 days while samples from the 380,000 rad dose level showed a SPC of 46,000 per gram and an AC of over 2 million per gram after 211 days. Spoilage appeared to be due to the anaerobes.

b. Snap Beans: The initial SPC of 100,000 per gram and AC of 240,000 per gram rose to over 20 million per gram and 200 million per gram, respectively, in 14 days. Irradiation to 690,000 rad held the SPC to less than 3000 per gram in 115 days, but the AC increased to 3 million per gram in only 63 days. A dose of 1.2 megarad held the SPC to 400 per gram for 140 days, but again the AC reached more than 2 million per gram in only 77 days. In addition, microscopic examination showed large numbers of yeasts present in the later stages of storage. The refrigerated shelf-life of these vacuum-packed blanched snap beans was extended by a factor of five after irradiation at 690,000 rad. This favorable result is tempered by the fact that color, texture, and flavor of the irradiated samples were decidedly inferior to the unirradiated. Other contractors¹² found that after one month storage at 40° F., snap beans irradiated at 930,000 rad were bleached to a light green, had an unpleasant sweet odor, and a non-characteristic flavor.

c. Baby Lima Beans: Counts were not made until the third day of storage when the SPC and AC were 1 million per gram, and 350,000 per gram, respectively. After 24 days the control SPC had risen to 100 million per gram. The control AC, however, took only 10 days to reach 9 million per gram. Irradiation to 450,000 rad reduced the counts. The SPC was only 1000 per gram after 180 days although the AC was 600,000 per gram in 75 days. Samples given a dose of 690,000 rad showed an SPC of 200,000 per gram in 159 days, and an AC of 10 million in only 68 days. Both of these counts are considerably higher than the samples at the lower dose of irradiation. The investigator had no explanation for this anomaly. The anaerobes also tended to die off in longer storage with the lower dose samples showing no recoverable anaerobes in 152 days, and the higher dose AC reduced to 20,000 organisms per gram in 159 days. Molds were not reported in any of the three products since they had been packed under vacuum. These experiments showed that the refrigerated shelf-life of blanched lima beans, irradiated to 910,000 rad, was extended seven times. Acceptance ratings of the irradiated lima beans were generally lower than the control samples and the texture was

softer. The characteristic green color of beans decreased with irradiation and storage. Further experimentation to determine the most suitable level of dosage is indicated.

Beets: Results with beets were most encouraging. The threshold dose for beets was found to be 279,000 rad.¹⁵ Detroit Dark Red Variety beets that had been cooked, skinned, sliced, and packaged in polymylar envelopes, and irradiated at 930,000 rad retained their flavor through one month's storage at 40° F. In fact they had a freshly cooked beet flavor little different from that with which they started. Beets irradiated at this level held up in storage for four months without significant loss of color and flavor. This would appear to be about the limit of storage life since in the fifth month of storage the flavor became more sweet and flat than formerly. In addition, the polymylar package started to delaminate at this period of storage¹².

Broccoli: Several experiments have been carried out on broccoli with varying results. According to one investigator¹⁷, broccoli appeared to derive little or no benefit from low doses of gamma irradiation and the color, flavor, odor and texture were adversely affected by higher doses. Another contractor¹², however, reported that broccoli, blanched for two minutes and irradiated at 695,000 rad, was acceptable after 27 days storage at 40° F. The irradiated samples were bright green in color, had a slightly flat taste, but no off-flavor, and showed no mold or deterioration.

Brussel Sprouts: Brussel sprouts, blanched in boiling water, packaged in polymylar, and irradiated at 695,000 and 930,000 rad developed a strong off-odor and flavor after two weeks' storage at 40° F.¹²

Carrots: Kertesz¹⁵ concluded that the threshold dose for carrots can be set at 106,000 rad. Dehydrated carrots irradiated at a slightly lower dose were found to be very acceptable by Wruk²¹.

Cauliflower: Off-flavors were produced in cauliflower irradiated at 100,000 rad and it was rated unacceptable by a panel¹¹. However, other investigators¹² found that blanched cauliflower packaged in polymylar envelopes and receiving 695,000 and 930,000 rad rated within the acceptable range. The samples were rather flat in taste when compared with the controls, indicating that further experimentation on cauliflower is required.

Corn: Corn appeared to respond well to low-dose irradiation. Blanch-ed corn on-the-cob, sealed in tin cans, flushed with nitrogen, and stored at 35° F., was held for 305 days. Panel ratings for the nitrogen-packed corn declined very little as the irradiation increased up to 1 Mrad. When these samples were rated for acceptability, the panel scores were as high after 300 days, as they were initially after 36 days. By contrast, the non-irradiated controls spoiled completely within this time. It was postulated that adding calcium chloride or ascorbic acid to the blanch-ing water would further benefit the corn, but no significant improvement was observed by using water alone¹⁷.

Sweet corn irradiated in husks at 500,000 rad and stored for 16 days at 40° F. was scored higher by taste panels than corn without husks. There was a trend toward improvement in taste preference as the dose increased up to 500,000 rad²⁰. Studies²¹, showed effective mold control.

Cucumbers: Loss of texture and offensive odors were detected in cucumbers receiving less than one million rad. No change in color was noted at this dose¹³.

Peas: The results here show a net advantage. Although softening of peas in pods was evident at 500,000 rad, after 11 days storage peas irradiated at a lower dose, 300,000 rad, were green and fresh. A slight decrease in acceptance was noted as the dose increased¹⁹. It was reported elsewhere¹⁸ that the shelf life of fresh green peas blanched for 6 minutes and packaged in cellophane bags, was extended up to 15 days by irradiation at 300,000 rad. In stabilization studies¹⁹, green peas showed no mold in 40° F. storage after 11 days and 16 days, respectively, at dose levels of 300,000 and 500,000 rad. Control samples and vegetables given 100,000 and 200,000 rad showed much mold.

Radishes: The data on radishes are partly encouraging. All irradi-ation doses except 93,000 rad affected the radishes; the 465,000 and 930,000 rad samples were reported to be soft, had a poor flavor, and were off-color²¹. At 93,000 rad the radiated radishes equalled the control samples in acceptability.

Lettuce: Lettuce irradiated at 46,500 and 139,500 rad was con-sidered very acceptable. Above this dose, off-flavors, discoloration, and texture changes were noted²¹.

Parsley: Parsley irradiated at 930,000 rad was considered acceptable²¹.

Sweet Potatoes: Radiation increased susceptibility of soft rot in this vegetable. Within the range of 46,500 rad and 279,000 rad, for example, irradiation increased susceptibility to Rhizopus nigricans (soft rot), as compared with non-irradiated controls. Heightened susceptibility of irradiated sweet potatoes to decay appeared to stem from their inability to form protective wound periderm tissue² after being irradiated.

Spinach: Fresh spinach packaged in polymylar and irradiated at 930,000 rad was acceptable up to 18 days of storage at 40° F. Blanched spinach (1-1/2 min. in boiling water) irradiated at 930,000 rad, and subsequently stored at 40° F., was in good condition at the end of 12 days. The leaves were distinct, the color bright, dark green, and the flavor, though sweet, still resembled the characteristic spinach flavor¹².

Tomatoes: In firm ripe tomatoes, artificially inoculated with Alternaria tenuis, a dose of 279,000 rad delayed the appearance of rot for ten to eleven days at 70° to 75° F. Non-irradiated controls showed the symptoms of rot after three days. At dosages below 279,000 rad, rot appeared proportionately faster, but at 46,000 rad no appreciable difference existed between the treated tomatoes and the controls². Green and pink tomatoes ripened erratically after 300,000 rad of irradiation. The organoleptic quality of ripe tomatoes declined progressively as the radiation dose advanced over 200,000 rad²⁰.

In other microbiological studies, the effectiveness of radiation was determined for tomatoes, using both normal¹⁹ and inoculated samples⁶. A dose of at least 500,000 rad was necessary to control mold and rot in both series, although the length of storage was considerably less in the samples inoculated with rot caused by Alternaria tenuis. Normal unirradiated controls and those given 50,000, 100,000 and 300,000 rad molded in 30 days at either 50° or 70° F. In the inoculated series the control samples and 50,000 rad samples rotted in 3 days at 70° F. Those given 300,000 rad took 10 - 11 days to rot, whereas those given 500,000 rad showed no rot in 12 days. Normal tomatoes irradiated to 500,000 rad showed no mold at 50° F. in 30 days, but did at 70° F. Finally in 53 days the 50° F. samples were also molded.

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CHAPTER 4

RADIATION PRESERVATION OF FRUITS AND FRUIT PRODUCTS

More than any other food commodity, fruits are preferred in their natural state. Low-dose radiation processing, which can extend their marketable shelf-life without altering their desirable fresh qualities, has special application in this commodity area.

Research results were not always consistent, but general trends indicated that from 200,000 to 800,000 rad materially increased the shelf-life of fruits by two to ten times, under various storage conditions.

Specific fruits showing promise of benefit through low-dose radiation include strawberries, grapes, peaches, tomatoes, and citrus fruits.

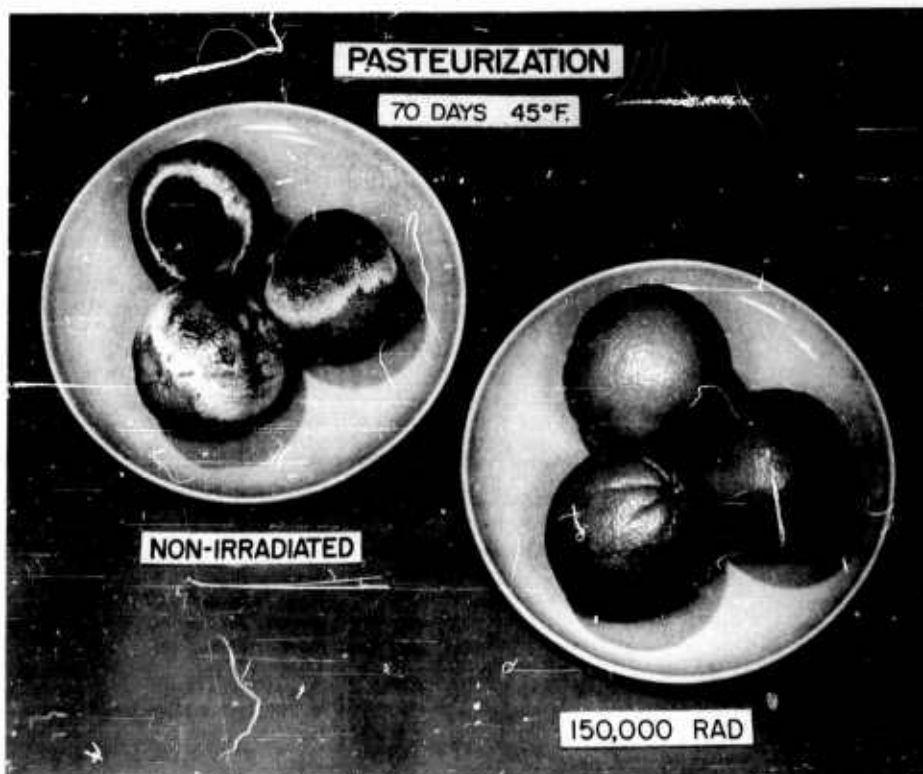


Figure 4-1. Low-dose irradiated oranges remained fresh 70 days at 45° F.

Considerable research has been done in low-dose radiation of fruits and fruit products in the area of 100,000 to 1,000,000 rad. Radiation stabilization studies on fruits included normal and inoculated packs in simulated commercial-size lots, as well as laboratory-scale tests. Complete inactivation of the pathogens was not feasible because high doses produced intolerable textural and skin color changes. In considering low-dose radiation applications, the length of holding without incidence of infection or visible radiation injury bears a direct relation to the dose received, temperature of storage, age of infection, nature of the suspect, and the organism involved. Results of studies on the effects of low-dose radiation on a large number of fruits include:

Citrus Fruits: Major cause of spoilage in citrus products are generally attributed to surface attack by the *Penicillium* molds, *P. digitatum* and *P. italicum*, and occasionally by *Alternaria citri* and *Diplodia natalensis*. Consequently, Quartermaster Corps research in this product area has centered primarily on the effects of ionizing radiations in controlling the growth of these organisms. Considerable experimentation on lemons and oranges inoculated with dense conidial suspensions of these molds has been undertaken. Radiation sensitivity of these microorganisms was also tested in synthetic media under controlled conditions.

The technological aspects of citrus irradiation studies have for the most part been concerned with radiation-induced changes in odor, taste, texture, and color. In some work, consideration was given to vitamin retention, changes in acid content, and pectin degradation.

Oranges: In the range of 40,000 to 275,000 rad, the rate and amount of decay of Florida Valencia oranges were inversely related to dose; the higher doses resulting in fewer infected fruit and a longer interval before decay appeared. Undesirable changes in texture and rind color were found following dosages of 450,000 rad or higher, after eight days. Only a trace of injury was noticed at 275,000 rad. Internal injury in the form of a watery texture was present at 900,000 rad, but not at 450,000 rad, or lower. At doses of 200,000 and 300,000 rad natural rind color was retained initially, but slight browning developed after 26 and 15 days, respectively, at 70-75° F. Browning was further intensified as doses increased from 500,000 to 1,000,000 rad. At these doses the rinds were also deeply pitted and roughened. Degradation changes during storage at 55-58° F. were similar in nature but occurred at a slower rate^{6, 9, 15}.

From experiments to determine the influence of different dose rates, it was found that flux rate bears an inverse relation to the rate of fruit decay. High gamma fluxes were more effective than low fluxes in retarding decay¹³.

In general, the findings are encouraging; namely, the useful life of oranges can be extended 2-to-3 times with 250,000 rad³⁵.

Lemons: Irradiation of lemons within the range of 150,000 to 200,000 rad prevented rotting by P. digitatum without injury for about 12 days at 75° F. and 17 days at 55° F. Unirradiated controls began to rot after 3 days. Doses required to kill fungus caused skin discoloration and softening. The shelf life of lemons inoculated with P. italicum was extended to 15 days at 75° F. and 17 days at 55° F. after 150,000 rad, whereas unirradiated controls showed some decay in 3 days¹⁵. Irradiation of lemons at 140,000 rad in commercial size lots, using cartons of 11x11-1/2x17-inch dimensions, was less successful than irradiation of small size samples. Those irradiated in the large lot became pre-disposed to green mold infection and Alternaria black rot⁸.

Grapefruit: No discernible changes were noted after treatment with 500,000 rad⁴².

Processed citrus products: One megarad was required for destruction of yeasts in orange juice⁴⁴.

Lemon juice concentrate given the same dose was considered acceptable⁴². Cold pressed lemon oil evidenced little or no organoleptic change after irradiation to 10,000 and 1,000,000 rad⁵⁰. In another study²¹, fruit salads consisting mainly of peeled citrus fruit sections showed off-flavor at 100,000 rad; whereas 500,000 rad was required for significant extension of shelf life. Application of additives and irradiation in the frozen state failed to eliminate off-flavor.

Some attention has been given to the effects of ionizing radiation on the chemical constituents of citrus commodities. In the case of orange juice, carbonyl compounds increased rapidly at doses up to 500,000 rad, with small but steady increases following at higher doses⁴⁵. Pigments comprising the color of orange juice were not measurably affected by doses up to one megarad⁴⁴.

Degradation of pectin isolated from irradiated lemon peels increased with dose. Irradiation with 0.6-Mev electrons resulted in less pectin breakdown than irradiation with 0.1-Mev electrons⁵⁰.

Oranges, inoculated with a P. italicum mold culture, showed mold decay in only 4 days at 75° F., whereas, inoculated fruit receiving 200,000 rad developed no mold in 20 days. At 41° F., the shelf-life of the controls was 15 days. The samples irradiated with 150,000 to 300,000 rad showed no mold in 65 days¹⁴.

In a similar study with lemons stored at 75° and 55° F., the inoculated control samples molded in 3 days at both temperatures. A radiation dose of 150,000 rad extended the storage life to 15 days at 75° F. with no observable mold; at 55° F., there was no molding in 17 days. Much higher doses were required to retard old or established infections than young or incipient infections¹⁴.

In a related study with P. italicum on oranges, it was of interest to note that the rate of gamma flux appeared to be inversely proportional to both the rate and total incidence of the fruit decay. Thus, at levels between 125,000 and 182,000 rad the rate of decay increased as the rate of flux decreased from levels of 40×10^3 , 20×10^3 , and 8×10^3 , to 3×10^3 rad per minute¹². A similar phenomenon had been observed earlier by the same contractor in pure culture studies on the organism causing potato leak, Pythium debaryanum⁸. This phenomenon has not been observed by any other investigator.

Radiation at 200,000 rad substantially reduced mold in sections of fresh lemon peel that had been heavily inoculated with P. italicum and P. digitatum; both types were killed at levels between 600,000 and 1 million rad. However, the higher doses softened the whole lemon⁴⁹.

When pure cultures of the organisms causing citrus spoilage were tested for radiation resistance, it was found that 24-hr. cultures of Penicillium italicum and P. digitatum on Tochinal's medium were destroyed by 120,000 to 160,000 rad¹⁵. Two of the three important stem-end rotting organisms were considerably more resistant. Of these, Diplodia natalensis, grown on Tochinal's medium, required 465,000 to 891,000 rad for destruction; when grown on Czapek's medium, 256,000 to 465,000 rad were sufficient⁹. Both in vitro and in vivo Alternaria citri required doses of 470,000 to 500,000 rad for inactivation¹⁵, Phomopsis citri failed to germinate in Czapek's medium when subjected to a dose range of 148,000 to 215,000 rad, although a lethal dose was in excess of 244,000 rad when Tochinal's medium was used. Doses in the range of 44,000 to 96,000 rad suppressed colony growth of this latter organism when applied to the conidia or young hyphae¹¹.

Strawberries: Six varieties of strawberries - Kasuga, Lindalicious, Marshall, Robinson, Shasta and Sparkle - were irradiated at 100,000, 200,000 and 300,000 rad and stored at 40° F. All varieties showed an increase in shelf life with increases in dose, but organoleptic quality declined progressively as the storage period was extended⁴⁶. The quality-preference scores (calculated by equating sensory scores with percentage of non-decayed berries) declined more rapidly for non-irradiated controls than for those given 200,000 or 300,000 rad. However, at the higher dose, many berries became peculiarly spongy; the sponginess became more apparent as the storage period lengthened. The different varieties showed varying susceptibility to softening and bleaching, suggesting that post-irradiation keeping quality may perhaps depend on the inherent firmness of different varieties. It was concluded that 200,000 rad was optimum for controlling mold, and retaining desirable characteristics of the berries.

Of the varieties tested, Kasuga and Sparkle appeared most adaptable to radiation processing. Experiments on the influence of strawberry maturity indicated the green tip stage to be best; fully ripe berries become soft and spongy, and unripe green berries failed to ripen after radiation⁴⁶.

A separate study with Shasta strawberries confirmed the optimal dose as 200,000 rad. The microbiological shelf life at 37° F. was extended to beyond 40 days at this dose level. Appreciable loss of sweetness and color was apparent after 30 days³⁶.

Attempts have been made to extend further the useful life of strawberries through combining low-dose irradiation with application of mold inhibiting chemicals. Best results were obtained with sorbic acid, Captan, DHA-S, and Dovicide A⁴⁶.

Experiments to ascertain the influence of dose rate in the range of 1 megarad to 5.5 megarad per hour showed no consistent trends with respect to sensory qualities⁴⁷. In another study, it was found that a dose rate of 1.0 megarad per hour was less destructive to ascorbic acid than 5.5 megarad per hour when a total of 100,000 rad were applied. When 500,000 rad were given, fast and slow rates were equally destructive⁴¹.

In order to determine the potential susceptibility of irradiated strawberries to texture damage during cross-country transportation and handling, simulated transit tests were conducted employing Shasta strawberries irradiated to 100,000 and 200,000 rad under an 8-Mev electron beam. No significant damage to texture was noted³¹.

In studies on Michigan-grown strawberries of the Premier variety, it was found that the refrigerated (34° - 36° F.) shelf life of vacuum-sealed berries was extended by a factor of one and one-half to two by irradiation at doses under 200,000 rad. Spoilage under these conditions was both microbiological and autolytic. Small losses in color, beta-carotene, and ascorbic acid were observed shortly after irradiation; additional losses were noted during post-irradiation storage¹⁷.

One experiment on strawberry preserves, employing graded doses of electrons up to and including one megarad, caused bleaching and flavor loss at the irradiated surface²². The effect of ionizing radiation on anthocyanin, the principal pigment of strawberries, was studied¹⁹. At 132,000 rad, 31% of juice anthocyanin was lost when irradiated in air, whereas under nitrogen the loss was reduced to 25%. Oxygen enhanced loss of anthocyanin with cathode rays, but had little or no effect with gamma rays. The pigment was less sensitive in strawberry juice than in citrate buffer of the same pH. Under various conditions, loss of pigment was reduced by (a) freezing, (b) sucrose (sufficient to raise the soluble solids content to 3 times normal), (c) ascorbic acid and (d) norhydroxyascorbic acid. Strawberry pigment irradiated in the dry state showed very little destruction¹⁸.

In microbiological tests, the naturally-occurring organisms found on irradiated strawberries were Cladosporium (Hormodendrum) (in 60% of the samples) and Botrytis (in 25% of the samples). Whenever present, Botrytis caused more severe spoilage than any other type of mold because of its profuse growth habits. Penicillium appeared only in the non-irradiated control fruits. Other types of mold (Alternaria, Aspergillus, Rhizopus, and Stemphylium) which were found sometimes growing on the fruits were of minor importance inasmuch as they were erratic in occurrence⁴⁶.

In one study, at the end of 49 days all strawberries were very moldy in the control samples and 100,000-rad batches, whereas those treated at 200,000 and 300,000 rad showed lesser degree of molding. Alternaria, Botrytis, Cladosporium (Hormodendrum), Stemphylium and Penicillium were present throughout with Botrytis and Cladosporium being the most prevalent. Growth of Penicillium was substantially inhibited by radiation whereas the growth of Cladosporium was not controlled by radiation alone. However, the latter could be eliminated by a treatment combining radiation with 2% Captan⁴⁶.

In another study, strawberries naturally contaminated with Botrytis cinerea (grey mold) and Rhizopus nigricans (Rhizopus rot) were treated with a dose of 200,000 rad. This treatment, combined with refrigeration, appeared to offer a successful method for prolonging shelf-life. Doses of 200,000 to 500,000 rad did not seem to affect the berries⁶.

From pure culture experimentation, it was learned that spores of both of these organisms were more resistant to gamma radiation than young, actively-growing mycelia, and the radiosensitivity of the spores was significantly influenced by the medium in which they were irradiated. Although the radiosensitivity of B. cinerea mycelium was not affected by the previous culture history, mycelium of R. nigricans was more radiosensitive when grown on Tochinai's medium than when grown on Czapek's medium. However, in another experiment, a higher percentage of conidia of Penicillium expansum survived irradiation in Tochinai's medium than in Czapek's.

In either medium, germ tubes of all irradiated spores were adversely affected in direct proportion to the radiation dosage in the range tested. While exact comparisons were not made at the same time with spores of other fungi, it was noted that, in general, the conidia of P. expansum and P. digitatum exhibited a marked radiosensitivity in contrast to conidia of such fungi as R. nigricans, B. cinerea, M. fructicola, and A. citri³.

A small amount of work was done in which jars of strawberry preserves were surface inoculated with P. roqueforti and the covered glass jars exposed to surface irradiation doses of electrons which penetrated the preserves to a depth of 1/8 inch. The irradiated samples were incubated for 30 days at 45° F. No visible mold growth was observed at this time. After one day's incubation, recovery counts were made on one jar from each lot. The initial load of 18×10^6 molds per jar was reduced to 600,000 per jar by 500,000 rad²⁴.

Peaches: Prairie Sunrise peaches, irradiated to doses of 100,000, 300,000, and 500,000 rad at temperatures of 40°, 70°, 100° and 130° F. were appraised after 10 days' storage at 40° F. Best results (based on preference scores equated with percent of non-decayed fruit) were obtained at the 300,000 rad level. Mold developed at doses lower than 300,000 rad, whereas 500,000 rad reduced the eating quality of the peaches. No consistent effect of radiation temperature was observed⁴⁶

Another experiment ³⁷, compared two peach varieties, one the Halberta, which is a hardy, canning variety, and the other, an Elberta, which is a more delicate type of fruit. Both could be irradiated up to 250,000 rad without off-flavors; above this level, off-flavors became increasingly noticeable.

In a study ³⁴ consisting of a larger number of varieties (Hale, Early Elberta, Late Elberta, Lemon Elberta, Riosa Gem, and a crossed Late-Lemon Elberta), irradiation to 300,000 rad, followed by storage at ambient temperatures, off-flavors were more prominent in the sweeter-tasting Elberta varieties. Hale peaches showed best retention of firmness but acquired a flat, mushy taste. Mold growth and decay incidence were almost identical in all varieties. Shelf-life of the irradiated peaches was extended approximately threefold, i.e., to 10-14 days at ambient temperatures and 30-45 days at 40° F.

In Michigan-grown peaches of the Hale Haven, Red Haven, and Elberta varieties, 130,000 to 200,000 rad of electron (1 Mev) radiation significantly reduced mold growth during storage at 31° - 32° F. Some additional surface bruising was noted, however, due to impact suffered during the irradiation ¹⁷.

Under conditions inducing severe infection with Rhizopus nigricans or Monilinia fructicola, a two-fold extension of the useful life of peaches was obtained with 200,000 to 250,000 rad ⁵. Induced infection with the yeast Torulopsis could be retarded by 150,000 rad ¹².

In another study ³³ on Elberta peaches employing very low doses, 20,000 and 40,000 rad were virtually ineffective. Doses in the 200,000 - 250,000 rad range were judged optimum in terms of least decay, and best retention of organoleptic qualities over a 20-day storage period at temperatures ranging from 50° to 80° F.

The use of fungicidal dips (Dowicide A and dehydroacetic acid) have demonstrated excellent potential for reducing radiation requirements for control of decay ^{34, 37}.

Irradiation of peaches in sealed containers containing activated carbon, reduced irradiation off-flavors and retarded catabolic breakdown ³⁴.

Experiments employing different packaging materials have indicated that the permeability and shock absorbing qualities of Kraft paper make it more suitable for packaging irradiated raw fruits than films such as Mylar C and PT-cellophane ^{34, 37}.

Peaches blanched in 50° Brix sugar syrup containing a small amount of ascorbic acid, showed no changes in color, odor, or flavor upon radiation with 250,000 rad and 1 megarad. Storage stability was directly related to dose received¹⁶.

Microbiological studies⁵ on the low-dose stabilization of peaches have been made by several investigators using both the inoculated pack technique and pure cultures. Fresh peaches inoculated with either Rhizopus nigricans (Rhizopus rot) or Monilinia fructicola (brown rot) were irradiated with a range of doses from 50,000 rad to 1 megarad and incubated at 80°-85° F. The minimal dose range found which significantly controlled Rhizopus rot was 200,000 to 250,000 rad; for brown rot the range was 150,000 to 200,000 rad. These dosages are within the limits which do not cause visible injury to peaches. When pure cultures of these organisms were tested for radiation sensitivity, the results indicated that the killing dose varied with the stage of development and was influenced by the medium in which they were grown. Under optimum conditions, conidia of Rhizopus rot survived 500,000 rad while the maximum dose allowing survival of brown rot conidia was 200,000 rad⁵.

In fresh peaches inoculated with Torulopsis yeasts which cause sour pit disease the rate of infection was slightly retarded by 150,000 rad, but not at lower doses. Yeasts reisolated from fruits irradiated at this level also grew at a retarded rate when transferred to malt agar. Again, the lower radiation doses had no effect¹².

In two experiments²³ conducted at the U. S. Army Quartermaster Food and Container Institute for the Armed Forces, water-packed, sliced, pie-type canned peaches were obtained from the steam exhaust box of fruit canning plant processing line. The first series of cans was irradiated at 0 to 2.0 megarad after chilling, and incubated at 86° F. Although viable organisms were sub-cultured after 10 and 30 days from samples which had received 250,000 and 500,000 rad, no viable organisms were recovered from any dose level after 6 months' incubation.

The second series of chilled cans was inoculated before irradiation with a mixed suspension of Torulopsis inconspicua, a butyric anaerobe resembling Clostridium pasteurianum, and Lactobacillus plantarum to a total of approximately 100,000 organisms per can. This cold-inoculated product was sealed under about six inches of vacuum to simulate the hot-packed product condition, irradiated at the same dose range and incubated at the same temperature. All of the inoculated controls were hard swells after 4 days' incubation and 5 of the 18 cans

at 250,000 rad swelled within 12 days. All of the organisms represented in the inoculum were recovered from these cans. Although in 7 months of incubation, no more of the inoculated cans swelled, viable organisms were recovered from the 250,000 and 500,000 rad dose levels after 42 days of incubation²³.

Grapes: Thompson seedless grapes irradiated to 100,000 and 200,000 rad were considered acceptable for marketing after 4 weeks at 40° F. Over 300,000 rad, fruits suffered a color change, possibly due to caramelization of sugars or by activation of an enzyme system. However, neither mold nor off-flavors were present. The control samples were inedible due to profuse mold growth⁴⁶. In another experiment, 500,000 rad appeared to control Botrytis cinerea inoculated in Tokay grapes, without much adverse effect on the fruit. At this dose no rot developed in 10 days after inoculation, while controls rotted in 4 days^{3,4}.

Nuts: Irradiation to 500,000 rad caused undesirable sensory changes in nuts⁶.

Sour Cherries: During tests¹⁶, Michigan-grown Montmorency cherries were gamma irradiated at levels ranging from 23,250 to 930,000 rad and subsequently stored at 40° F. The least spoilage was observed at 250,000 rad, with 60 percent of the fruits showing no discernible deterioration in 26 days. The unirradiated control samples spoiled within five days. The samples irradiated to 500,000 rad and above decayed from mold and rot after 2 to 2-1/2 weeks; predisposition to spoilage was probably due to radiation injury at the high doses.

Another laboratory⁴⁷ reported that two varieties of Utah-grown sour cherries, (Early Richmond and Montmorency), showed less mold during storage at 40° F. after radiation to 300,000 and 500,000 rad while little increase in shelf-life was achieved at 100,000 rad.

This same investigator irradiated a third cherry variety (Suda) at the firm-ripe stage, employing doses of 300,000 to 500,000 rad applied at temperatures of 40° - 130° F. After seven weeks' storage they were sorted and evaluated raw or cooked in 40 percent sugar.

Quality scores, (calculated by equating sensory scores with percent of non-decayed berries), increased with radiation dose, indicating the progressive inhibition of mold at the higher dose levels. However, there was progressive degradation of the red pigment in the fruit juice at the higher radiation doses (300,000 and 500,000 rad)⁴⁶.

In studies on radiation-induced softening, the average threshold dose for softening was about 53,000 rad, ranging from about 28,000 to 71,000 rad for four different varieties.

However, no detrimental flavor and color changes were found in sour cherries irradiated up to about 550,000 rad, the highest level used in this study. In this range, respiratory activity measurements indicated only a slight and transitory effect on the O_2 uptake and CO_2 production. No varietal differences in respiratory response could be established. The increase in respiratory activity was observed during irradiation, but diminished rapidly after irradiation³⁰.

Sweet Cherries: Although little or no radiation injury was observed in sweet cherries given 100,000 rad, there was also no significant effect with respect to destruction of microbes. Doses of 300,000 rad yielded satisfactory results with respect to microbial control and avoidance of excessive injury. Increasing the dose to 500,000 rad produced adverse flavor changes as well as softening.

Microbiological examination of irradiated cherries stored eight days at 40° F. revealed Alternaria and Cladosporium (Hormodendrum) as the major causes of rot. Widespread incidence of Penicillium was also found in unirradiated cherries, but not in those which had been irradiated. Stemphylium and Botrytis were also found, the latter even in samples treated with doses as high as 300,000 and 400,000 rad^{46, 47}.

The efficacy of combining low-dose irradiation with fungistatic agents was also investigated⁴⁶. Dipping in sorbic acid solution prior to irradiation at 100,000 rad was more effective than radiation alone. At higher doses, however, the combination treatment was no more beneficial than irradiation alone.

The same investigators have also reported that doses to 200,000 rad retarded normal ripening during storage at 40° F.⁴⁶. Also, where two dose rates were employed, cherries irradiated at the faster rate were softer and more inferior in flavor than those given the same dose at a slower rate.

Apples: Golden Delicious, Red Delicious, and Northern Spy varieties irradiated at 50,000 and 100,000 rad suffered less spoilage over one year storage at 35° F. than those given 200,000 rad. Unirradiated control samples spoiled several months sooner than irradiated lots. Among factors affecting the keeping characteristics of irradiated apples were original quality and holding time between

harvest and irradiation¹⁵. Surface irradiation with 1 Mev electrons was ineffective in reducing mold growth in Wealthy and Double Red Delicious varieties stored at 31° - 32° F. after treatment with 130,000 and 260,000 rad. Noticeable skin discolorations occurred during storage of the Delicious variety¹⁷.

In experiments with Penicillium expansum inoculated apples 100,000 rad significantly reduced rot for six days of storage at 70°-75° F., but 200,000 rad were required for complete inhibition of rot over this period⁶. Doses of 300,000 rad and above caused notable damage in the form of internal core breakdown, changes in skin color, and softening^{3, 4}.

An extensive investigation³⁸ was conducted to determine factors influencing the quality of irradiated pie-type apple slices. These included variety, physiological maturity, and ripeness of apples; pre-irradiation preparatory treatments such as blanching and chemical treatments for control of browning, addition of firming agents and spices, variation in headspace gases, and sugar content of syrup; radiation dose level and temperature during irradiation.

Vacuum-packed samples receiving up to 1 megarad were all acceptable and generally superior to air-packed samples. Sulfite employed at 300-ppm bleached the apple slices and left an undesirable residual flavor. Color stability was optimum when slices were packed in a sucrose-sulfite solution and irradiated frozen. Mature apples yielded better products than immature ones. Best texture and flavor were obtained by blanching in a sugar and calcium solution. In some cases increasing dose from 0.5 to 1.0 megarad lowered acceptance; in other cases there was little difference between dose levels. Although changes in flavor, color, and texture of slices were noted during 6 months' storage at 75° F., these changes apparently had little effect on the preference scores of pies prepared from the slices³⁸.

Fundamental studies^{24, 25, 27, 28} on irradiated plant tissue have implicated the polysaccharides, pectin, and cellulose, in radiation softening of fruits and vegetables. Gamma radiation caused a decrease in the protopectin and total pectin substances while soluble pectin and pectates increased. These changes were accompanied by depolymerization of pectin and protopectin.

The threshold doses for softening of tissue from seven different varieties of apples ranged from 30,000 to 140,000 rad²⁶; for most varieties the dose was in the lower range. Threshold doses for

change in pectin and cellulose (as measured by changes in viscosity of standardized solutions) were also in the 30,000 to 40,000 rad range. Texturometer measurements of apple tissues irradiated at graded doses indicated that softening is a function of the logarithm of the dose applied.

An inoculated pack study was made to evaluate the radiation dose necessary to inhibit spoilage of apples. Vacuum packs of apple slices were inoculated with yeasts and molds isolated from spoiled packs or known cultures. The cultures used showed varying resistances to radiation. The dose necessary to control spoilage due to yeasts ranged from 500,000 rad to 1.5 megarad; for P. expansum, from 500,000 to 900,000 rad. Part of this variation was probably due to the variation in size of inoculum³⁸.

Elsewhere, another investigator showed that spores of P. expansum in pure cultures survived doses of 300,000 rad, but not 500,000 rad. As noted in other studies⁵, the degree of survival was dependent upon recovery medium used³.

Apricots: In one study⁴⁷ employing five varieties (Perfection, Hungarian, Wilson Delicious, Stella, and Chinese), apricots irradiated to 100,000, 300,000, and 500,000 rad scored as well, on a hedonic scale, as the unirradiated control samples. Nevertheless, some softening was noted particularly at the higher doses, and some varieties developed a brownish skin discoloration. Re-examination after 8 days at 50° F. revealed some mold growth in the controls and those given 100,000 rad. Although injury in the form of discoloration, bruising, and softening increased during the 8-day storage period, the irradiated samples were still acceptable to the panel.

A later study by the same investigator⁴⁶ employed two varieties (Chinese and Moorpark), longer storage periods, and two irradiation dose rates. During the first 21 days of storage, the Chinese apricots irradiated at the faster rate were superior. This was reversed during the later portion of the storage period with the apricots irradiated at the slower rate being preferred. Fruits of both varieties irradiated to 200,000 rad remained in good condition up to 42 days at 40° F. Those given 400,000 rad deteriorated shortly after being placed in storage. Mold growth at this dose was attributed to predisposition of the fruits to mold attack due to excessive tissue softening. In another experiment³¹, apricots of the Royal variety were markedly softened by electron irradiation at doses in excess of 200,000 rad. Respiration rates of fruits measured immediately after irradiation up to 600,000 rad increased in proportion to dose. This, however, did not appear to alter the time for onset of the climacteric.

Blueberries: Michigan-grown blueberries in polyethylene bags were radiated at seven levels ranging from 50,000 to 500,000 rad and stored at 75° F.¹⁴ The lots receiving 50,000 to 250,000 rad showed a slight reduction in decay after 16 days of storage; however, after 28 days of storage all lots showed about the same amount of decay as the non-irradiated control. Radiation to 300,000 and 500,000 rad resulted in softening of the berries and abnormal red color in the flesh after 16 days' storage, whereas 250,000 rad produced only slight injury after 28 days' storage. In pure culture studies, several pathogens isolated from decayed blueberries were irradiated *in vitro*. Among these were species of Alternaria, Mucor, Aspergillus, Monilinia, Botrytis, Pullularia, and Phoma. The radiation sensitivities of these cultures indicated that the killing dose was below 500,000 rad.

In other tests¹⁷, blueberries which were gamma irradiated in evacuated cans to 90,000 and 140,000 rad became unacceptable after storage at 35° F. for 56 and 162 days, respectively. This represented more than a two-fold extension of refrigerated shelf-life. Irradiated samples were firmer than control samples and lacked both characteristic blueberry flavor and tartness. Their interior flesh color was redder than that of unirradiated controls, likewise the liquid exudate was more red and opaque than the corresponding control. Hunter Color Difference Meter readings were in agreement with the visual observations.

Freshly picked and washed Michigan blueberries were canned under vacuum before being irradiated to 0, 90,000, and 140,000 rad. For these samples, spoilage after storage at 34°-36° F was due to bacteria rather than molds. The initial standard plate count was 270,000 organisms per gram and after 70 days, the controls showed counts of over 4 million per gram. The counts of the irradiated samples did not exceed 5000 per gram, however, the blueberries became unacceptable due to autolysis at 56 days for the lower dose, and 162 days for the higher dose¹⁶.

Pears: It was reported³¹ that electron irradiation of Bartlett pears at 100,000 and 200,000 rad delayed ripening by two to four days, and no other radiation-induced changes were noted. Although the respiration rate of treated pears increased immediately after treatment, it declined slightly on holding, and underwent the climacteric at about the same time as the control fruit. At 500,000 rad, however, pears developed brown, mushy areas about 1/4 inch deep on the side directly under the beam. These symptoms appeared after 24 hours at both 41° F. and 68° F. storage.

A second study⁴⁰ reported that ripening of green Bartlett pears was not impaired at 200,000 rad. Only slight changes in odor and appearance and moderate changes in flavor were noted. The keeping qualities of the pears were improved, with good condition being retained for two weeks at 70° F. Above 200,000 rad the fruit deteriorated rapidly.

Another group of investigators¹⁷, reporting results of storage tests in home refrigerators, showed that 100,000 rad surface radiation (1-Mev) had deleterious effect on ripe Bartlett and Kieffer pears. The irradiated pears became mushy and discolored while the control samples were still edible after 46 days, although slightly bitter. The radiation injury was attributed to the pears being irradiated in the "dead ripe" maturity state. Surface mold growth was suppressed.

Cranberries: The dose of 100,000 rad was ineffective in reducing fungal rot of cranberries during 22 days' storage at 70° - 75° F. The number of rotted berries was appreciably reduced by 200,000 - 300,000 rad, and complete inhibition of fungal growth was achieved with 400,000 rad. No radiation injury was evident at 100,000 rad; above 150,000 rad injury was proportional to dose, taking the form of soft, spongy texture, bleaching of skin color from deep red to light pink, and extreme reddening of flesh color^{7, 8}.

Dates: Microbiological spoilage of dates was controlled by 500,000 rad without impairment of flavor⁶.

Pineapple: Microbiological spoilage of pineapple chunks could be retarded by 500,000 rad and above, however, off-flavors developed at the 100,000 rad level and the product was ruled unacceptable^{16, 21}. A sweet, sharp, bitter, flavor, as well as a strange uncharacteristic flavor, developed. Attempts to eliminate or reduce off-flavor by including additives or irradiating in the frozen state were not successful²¹.

Prunes: Molds were destroyed by 930,000 rad without changes in acceptability⁴³.

Raspberries: Mold growth in black raspberries was controlled by 300,000 - 500,000 rad without loss in sensory quality. The berries remained edible during 11 days at 40° F.⁴⁷

Rhubarb: The dose of 930,000 rad markedly improved the bacteriological keeping quality of rhubarb sauce (McDonald Strawberry Variety) packed in polymylar envelopes. However, the delicate

bright rose color of this premium variety was lost after radiation to 279,000 rad, and eventually resembled the green color of rhubarb varieties which have little red pigment. No other organoleptic changes or spoilage took place in irradiated rhubarb sauce for four and a half months, whereas unirradiated controls were molded after 19 to 27 days¹⁶.

PACKAGING FOR FRUITS

In packaging studies^{36, 48}, the critical importance of considering the "living" nature of raw fruits has been brought into focus and the need for materials which will provide the oxygen required for normal respiration emphasized. Another factor to be considered is the necessity for avoiding localized moisture accumulations which tend to promote mold growth. Berries packed and stored in perforated cans were superior to those in hermetically-sealed cans⁴¹. In experiments comparing other packaging materials⁴⁶, greater fruit survival was obtained with Mylar C than with polyethylene. This may have been due to greater moisture condensation on the inner surface of the polyethylene bags, a condition more conducive to microbial growth. Of many packaging materials tried, Kraft paper bags gave best results. This was attributed to the absorbence and permeability qualities of paper³⁶.

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CHAPTER 5

RADIATION PRESERVATION OF MISCELLANEOUS ITEMS

As an example of miscellaneous products treated with irradiation, dutched cocoa and chocolate syrup were exposed to doses up to 600,000 rad.

Four different batches of cocoa were selected; two with a high count of 30,000 and 38,000 per gram and two with a low count of 3,000 and 6,000 per gram at approximately two levels of fat (20 and 14%). In the lower count samples, 100,000 rads reduced the count to less than 500 per gram. The higher count samples required 300,000 rad to accomplish this reduction. To reduce the counts to less than 10 per gram required 300,000 and 600,000 rad. Inasmuch as the higher doses had an undesirable effect on quality, it was believed that the 100,000 rad dose would sufficiently reduce the bacterial load to allow practical storage with minimal effect on quality factors, especially if the original product was a good quality cocoa ¹.

Normal and inoculated chocolate syrup were the test products in another set of experiments. Again increased protection resulted from increased radiation levels and the 100,000 rad dose appeared practical if the syrup count was low initially ².

Cereal bars withstood 50,000 rad without adverse changes in their acceptability. The same held true for flour.

Bread, crackers, rolls, and other bakery products have also been benefited by low-dose radiation.

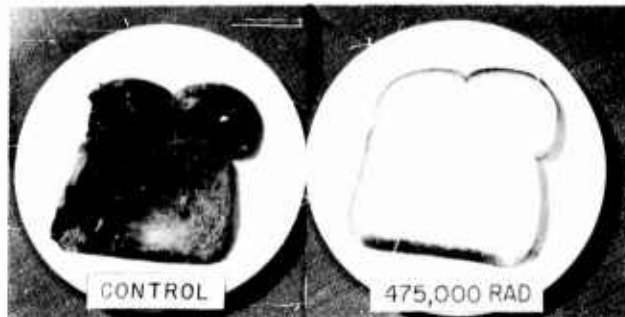


Figure 5-1. This bread was photographed after 60 days' storage at room temperature. Left, is the unirradiated control sample; right, shows the superior keeping qualities of bread irradiated with 475,000 rad.

The first complete dinner of irradiated foods outside of the laboratory was demonstrated at the request of the Subcommittee on Research and Development of the Joint Congressional Committee on Atomic Energy, and included a number of miscellaneous commodities. The dinner was served to the group as an experimental project on 29 June 1956, in the Speaker's Dining Room of the National Capitol.

The menu, comprising foods that had been given both low-and high-dose irradiations, included the following miscellaneous items in the "pasteurizing" level: cabbage, carrots, strawberries, and lemons given from 0.2 to 1.0 megarad to extend refrigerated shelf life; hearth rolls given 0.75 megarad and kept at room temperature for 3 months; date nut bread given 0.25 megarad and kept at room temperature for 1 week. A good organoleptic score was given by this most distinguished taste panel. None of the products was rated unacceptable.



Figure 5-2. This more recent experimental meal has been served to taste panels and received acceptable ratings.

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CHAPTER 6

PROTECTING FOOD AGAINST INSECT DAMAGE

Low-dose radiation of foods to control insect infestation appears to be a particularly practical and useful application. Insect infestation of cereal grains, cereal products, and military ration components therefrom has long been a serious problem in this country, as well as in tropical and subtropical areas. Prevention of insect contamination can be extremely costly and is often impossible.

Conventional methods of pest control employ extremes of temperatures, insecticidal sprays, dusts, aerosols, and fumigants. The increasing problems of the development of resistance to insecticides by insects and of the stricter regulations forbidding contamination of foods by pesticidal residues give greater impetus to the search for more effective methods of insect control.

Two potential methods of control using ionizing radiation are evident: indirect control of a pest species by the release of sterilized adults³ and direct irradiation of infested products⁴. The merits of these two methods have been published⁶. The first method will not be discussed further in view of its attendant requirements for success. Methods related to preservation of food based on irradiation are desirable in several respects, for example, packaged products can be disinfested because the radiation can penetrate the package. General conclusions may be drawn from the evaluation of existing data. In general, while X-rays appear to differ in effectiveness, the relative effectiveness of gamma and high energy electrons are of the same order of magnitude⁸.

1. EFFECT OF RADIATION ON INSECTS

Experimental data have established the effectiveness of low-dose radiation in insect control^{1, 2, 6, 8, 10, 11}. Investigations of the effects of radiation on various insects have demonstrated that the immediately lethal doses (within 24 hours) range from 300,000 rad to 600,000 rad and that lower doses will shorten the life span of insects^{10, 12}. In these studies it was found that doses ranging from 25,000 to 50,000 rad destroy some insect eggs, prevent the development of later stages, impede reproduction of the adults or cause premature deaths. These doses cannot be depended upon for complete disinfestation; however, they can reduce the severity of the infestation, thereby providing a partial disinfestation.

In other studies, it was found that adult flour beetles of the species Tribolium castaneum ceased feeding for two days after irradiation with 27,400 rad or more of high energy electrons. The beetles resumed feeding between the second and seventh days; the amount of feeding depended on the dose of radiation applied.¹³

The foregoing studies included such species of insects as the confused flour beetle (Tribolium confusum), yellow mealworm (Tenebrio molitor), sawtoothed grain beetle (Oryzaephilus surinamensis), lesser grain borer (Rhizopertha dominica), cigarette beetle (Lasioderma serri-corne), cadelle (Tenebroides mauritanicus), common house fly (Musca domestica) as well as others.

2. EFFECTS OF IRRADIATION TREATMENT ON FOODS

The selection of ionizing radiation as a control method will depend on whether insect control can be achieved by a dose of radiation that will not abrogate the essential characteristics of the commodity. Because the effect of radiation varies with the commodity and species of insect involved, each infestation problem must be considered separately.

a. Wheat: Wheat irradiated at 250,000 rad produced a satisfactory loaf of bread with a slight but not objectionable flavor.⁹

b. Flour: Studies with wheat flour demonstrate that the off-flavor threshold occurs at about 20,000-50,000 rad. Flour irradiated at these doses produced satisfactory bread and cake; however, the cake had a slightly reduced volume. Above 50,000 rad the off-odors became more pronounced; the bread and cakes became gelatinous and brown in appearance. The degree of undesirable characteristics increased with increasing radiation dose.^{5, 9}

c. Compressed Cereal Bars: Compressed ration cereal bars irradiated at 50,000 rad were acceptable and indistinguishable from the non-irradiated control. After one year's storage at 100°F. both the irradiated and non-irradiated bars were still acceptable. There was no indication of latent radiation effects.⁹

d. Oats: Irradiation of oats at 50,000 and 1,000,000 rad was apparently without great effect on oat stability or nutritive value. Other than a slight flavor change, there was no evidence of any material difference between the unirradiated and irradiated oats as judged by storage performance of products made from them. This included assays for several important amino acids and vitamins. In addition, a sixty-day rat feeding test failed to indicate any evidence of acute toxicity.⁵

e. Spices: Of a group of spices irradiated at 150,000 rad cinnamon alone was affected, showing a slight bitterness at this dosage but not at 75,000 rad. Other spices irradiated in this group were ground paprika, nutmeg, chili powder, marjoram, red pepper, cayenne, ginger, coriander and anise seed ⁷

Commercial radiation facilities, processes, and protocol of processing remain to be established. The removal of insect fragments from commodities to conform with established purity standards and attendant specifications is still another problem.

3. PACKAGING CONSIDERATIONS

As in conventional disinfestation methods where there are no chemical residues ionizing radiation would provide no deterrent to subsequent reinfestation, therefore, this new technique must be integrated with packaging systems. The ability of insects to penetrate packaging barriers varies widely from species to species, some being incapable of defeating even the most modest container while the cadelle by contrast can penetrate 0.002 inch aluminum foil. Entry by penetration by such insects is of special concern because once entry is accomplished further contamination by insects and microorganisms will follow. An additional hazard is posed by insect larvae hatching in the folds and creases of some packages and entering by way of microscopic holes in these areas.

Glass containers and tin-plate cans are immune to insect attack if well sealed. Wax dip coatings and sandpaper are also effective physical barriers if they remain undamaged. Practically all flexible fibers used or proposed for packaging material can be broached by certain food-infesting insects. Such materials and packages must be chemically or otherwise treated in order to be immune or resistant to insect infestation. Chemical treatments of packaging materials to prevent insect damage are commercially available. Studies of one effective treatment, pyrethrin-piperonyl butoxide treated paper, showed that it was not damaged by irradiation at 500,000 rad.¹⁰ At high-dose preservation levels it appeared that this treatment retained effective insect repellency for more than 2 years.¹⁰

Irradiation of waxes resulted in cross-linking and hardening of the wax,¹⁴ but any changes that could affect the insect resistance of waxes have not been encountered.

It has been shown that low-dose ionizing radiations are capable of insect disinfestation.

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PART III

ACCEPTABILITY OF FOODS PRESERVED BY LOW-DOSE RADIATION

The adaptation of low-dose irradiated foods to appetizing recipes such as shrimp creole, beef stew, chicken curry, and many others, is of primary importance because the rating given to prepared dishes served to taste panels is a strong indication of quality and acceptance.

A variety of precooked dishes, prepared from standard recipes, irradiated at 930,000 rad, and held at 40° F. for the storage periods indicated, developed little or no off-flavor and were benefited by low-dose radiation¹. Chicken Supreme, for example, was judged to be "Excellent" after 27 days' storage at 40° F.



Figure III-1. These appealing irradiated foods provide highly satisfactory menu items.

CHAPTER 7

RECIPES FOR "PASTEURIZED" FOOD ITEMS

Various dishes have been prepared with "pasteurized" foods for acceptability tests¹. Most of the products contained a number of flavorful ingredients. The evidence was not clear as to whether a protective effect was brought about by these ingredients or whether the generally strong flavor of the final product was sufficient to mask undesirable effects. The prepared foods were packaged in polymylar envelopes and irradiated to 930,000 rad at the Fission Products Laboratory. The various dishes, and acceptability ratings given by taste panels, include:

Barbecued Pork Chops: Irradiated barbecued pork chops were considered acceptable after nine months' storage at 40° F. Unirradiated samples spoiled after 13 days.

Beef Stew: The stew judged to have the best flavor consisted of one-half beef, one-quarter pork, and one-quarter veal, with only salt, pepper, and bay leaves for seasoning. After five and one-half months' storage at 40° F., this product was still acceptable; however, it was less flavorful than the fresh product.

Chili Con Carne: Chili developed no irradiation flavor and was considered excellent by the acceptance panel.

Shrimp Creole: A creole sauce, with rice, was prepared and added to the precooked shrimp, after which product was packaged and irradiated. After six months' storage at 40° F. it was still an excellent product. After nine months, however, the texture of the shrimp was such that when touched by a fork it fell apart.

Chicken Curry: No irradiation or off-flavor was detectable in this product after four months' storage at 40° F.

City Chicken: Veal or pork cubes arranged on wooden skewers, with gravy packaged separately, were acceptable after 8 months' storage at 40° F.; however, the flavor was somewhat flat.

Chicken Supreme: Chicken supreme, composed of cooked chicken, mushrooms, pimentos, cooked noodles, and seasonings, was prepared and packaged in polymylar envelopes. Immediately after irradiation the product was judged to be excellent; each ingredient was flavorful, and the noodles were still intact. After 27 days of 40° F. storage, the control samples were spoiled, but the irradiated samples continued to be in excellent condition. However, after four months' storage a rancid flavor could be detected; no other degrading was noted.

Hot Potato Salad: Potato salad has proven to be another satisfactory menu item. The potatoes used in the recipe were only partially cooked. Ingredients included bacon, onion, sugar cider vinegar, wheat flour, salt, and pepper. No discoloration of the product could be perceived after storage for four months at 40° F. Sensory examination showed that the potatoes had become somewhat rubbery and grainy in texture after this time. While the product was considered somewhat less desirable than potato salad prepared with non-irradiated potatoes, it was still satisfactory when served warm. Six months of storage showed no further changes.

Beef Swirls: The recipe for Beef Swirls consisted of ground beef, egg, tomato soup, onions, green pepper, cheese bread crumbs and seasonings. Although the recipe contained a high percentage of cheese and beef (two products which when irradiated separately developed off-odors and flavors), this dish was judged as "good" by a taste panel. The product had been stored for 3 months at 40° F.

Efforts were made to determine which ingredient, if any, was acting as a protector. To determine this, one ingredient at a time was tested. For example, several samples were prepared, and in each one a different ingredient was omitted---the egg in one, tomato soup in another, and so forth. These samples were examined organoleptically immediately after irradiation, and again after a storage period. The taste tests indicated that the best product was obtained when the complete recipe was used; the least desirable product was that made when the tomato soup had been omitted. This was the only product that had an irradiation off-flavor.

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PART IV

TECHNOLOGICAL ASPECTS

The ultimate success of the exploitations made in this new preservation concept depends upon converting into practical dimensions the basic knowledge and experimental findings on the action of low-dose ionizing energy on individual foods.

This conversion introduced additional technological aspects, which have also been investigated. Production facilities, a major initial factor, are of course, a commercial consideration; however, economic estimates, based upon knowledge gained through this research program, are presented in Part VI of this report.

Substantial work has been done in other technological areas, including research directed toward: assuring the wholesomeness of irradiated foods; retaining flavor, odor, texture, taste, and nutritional value; determining effective dosimetry systems; and developing suitable packaging materials. The overall results of this work have been encouraging, and significant findings are presented in the following four chapters.

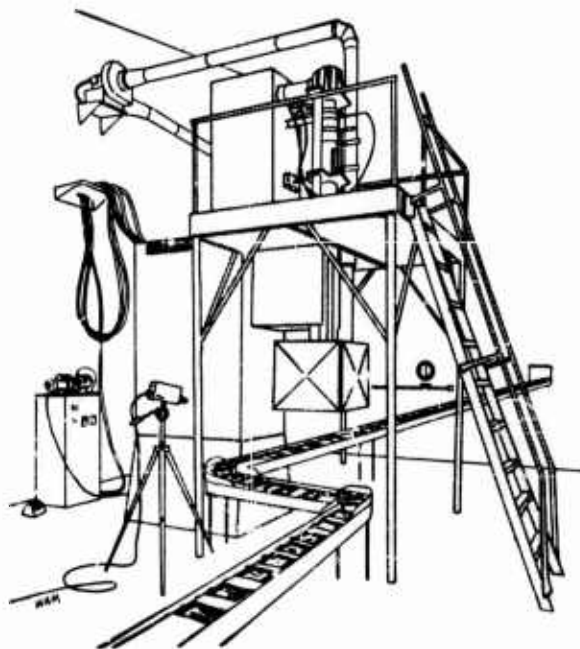


Figure IV-1. This typical experimental food processing line uses an electron accelerator, which has been found to be one of the most practical energy sources for applying ionizing radiations to food. The TV camera is used by the operator to observe the process.

CHAPTER 8

WHOLESOMENESS

Wholesomeness studies of irradiated foods were initiated at the Army Medical Research and Nutrition Laboratory (MR&NL) in 1948. These experiments, in which rats were fed irradiated food, indicated some destruction of vitamins, findings which were supported in similar experiments conducted later by Swift and Company, the University of Michigan, and Columbia University¹.

The results from some of the earliest wholesomeness tests of irradiated foods were inconclusive. Current evaluation of the nearly completed wholesomeness program appears to indicate that low-dose irradiation processing does not impair the wholesomeness of foods.

In 1954, a program was initiated, through research contracts with 13 universities and other research establishments, to determine wholesomeness of irradiated foods.

Considerable efforts have been directed toward retaining vitamins in irradiated foods and notable progress has been made. Results obtained thus far indicate that vitamin destruction need not be a deterrent to the preservation of food by low-dose ionizing energy. For example, foods can be irradiated in the frozen state to reduce the rate of diffusion of free radicals produced by the radiations. Use of this approach proved successful in reducing destruction of ascorbic acid.

From a nutritional point of view, the commercial application of low-dose radiation techniques, using suitable sources, probably can be considered a satisfactory addition to presently available methods for preserving some foods.

Another factor considered in determining the wholesomeness of irradiated food is the possibility of induced-toxicity. This was first investigated by experimentally-feeding irradiated food and unirradiated control samples to test animals for various periods of time. Short-term studies, subacute toxicity tests, were established and usually continued 8 weeks. Long-term animal-feeding studies²³ were also established. These lasted two years, or in the case of rats, through four generations, and were used to determine any obscure toxicity.

Factors such as growth, food consumption, lactation, size of litter, viability, and longevity were recorded. By 1958, concurrent or separate tests were also being run to assure that test foods did not provoke any spontaneous tumor formation, or carcinogenesis⁴. Significant findings from these tests are presented on the following pages:

1. Short-Term Animal Feeding

Since the objective of a short-term feeding study is to furnish a nutritionally adequate diet for the animal while simultaneously providing a large amount of irradiated food, 35 percent (dry weight) of the irradiated food to be tested is added to the basal diet^{2,5,6,7}. Most of the foods subjected to these short-term tests were given sterilizing doses of radiation but some low-dose items, such as potatoes and cereals, were also included. Evidence obtained from these early studies indicated the foods were generally wholesome.

2. Long-Term Animal Feeding

The long-term program to determine the wholesomeness of foods irradiated to "pasteurization" levels began in mid-1956 as part of a larger program which encompassed 22 foods. This total effort, funded by the Quartermaster Corps, and carried out by contractors selected and monitored by The Surgeon General of the Army, included 4 foods: flour, oranges, cabbage, and potatoes, in the "pasteurization" level and 18 items radiation-sterilized⁸.

Overall procedure in all cases involved the feeding of sizeable animal colonies for extended periods of time. Irradiated test items comprised from 16.7 to 35.0 percent of total diet. During the feeding period, the animals' general appearance and condition, hematology, size and weight, and reproductive capability were recorded. Upon completion of the study, gross pathology and histopathology were performed on each animal.

Most of the tabulation studies have been completed, except for the advanced pathology work. Results of these studies at "pasteurization" doses have been generally good. Pertinent information relative to these studies is tabulated in Table 8-1.

Oranges: At Vanderbilt University, investigators reported no evidence of toxicity as a result of feeding irradiated whole and peeled oranges to monkeys¹⁰.

Cabbage: Syracuse University studies show that there was no difference between the control and test animal group so far as consumption and utilization rate, reproductive capacity, lactational performance, longevity, and hematology are concerned. Some additional statistical studies are being pursued to pinpoint the cause of some differences in second generation growth and weaning rate¹¹.

The findings of workers at University of Georgia¹² feeding pasteurized cabbage to dogs for two years likewise indicate that this item is equivalent to the unirradiated control food in all aspects investigated, growth, weight maintenance, reproduction and lactation, and blood chemistry.

Flour: Oregon State College¹³ reports indicate that growth and other parameters measured in studies of rats fed irradiated flour continue to parallel those of the control animal group.

Likewise, dogs fed irradiated flour at the University of Illinois¹⁴ appeared to show no adverse effect in any factor, as growth, hematology, or reproduction.

Flour was a component of a mixed irradiated diet fed to rats at the University of Illinois²⁴. A hemorrhagic syndrome encountered in this study has been determined to have been due primarily to Vitamin K deficiency. Although further studies are not quite complete, there is no evidence that the flour processed by low-dose irradiation contributed to the syndrome.

Studies conducted at The University of Georgia¹², where "pasteurized" cabbage was fed to dogs for two years, also indicate that this item is equivalent to the unirradiated control sample in all aspects investigated, growth, weight maintenance, reproduction and lactation, and blood chemistry.

TABLE 8 - 1. Wholesomeness Feeding Studies

<u>ITEM</u>	<u>FEEDER</u>	<u>ORGANIZATION</u>	<u>TEST ANIMAL</u>	<u>DOSE (KILORAD)</u>
Whole Oranges *	Phillips, A. W.	Syracuse U.	Rat	139 and 279
Whole and Peeled Oranges	Blood, F. R.	Vanderbilt U.	Monkey	150 and 300
Peeled Oranges *	Phillips, A. W.	Syracuse U.	Rat	150 and 300
Cabbage	Haie, M. W.	Georgia Coastal Exptl. Station	Dog	279 and 558
Cabbage *	Phillips, A. W.	Syracuse U.	Rat	279 and 558
Flour	Tinsley	Oregon State Coll.	Rat	37.2 and 74.4
Flour	Reber, E. F.	U. of Illinois	Dog	37.2 and 74.4
Flour * *	Calandra, J. C.	Bio-Test Labs., Chicago	Mouse	37.2 and 74.4
Potatoes	Teply, L. J.	Wisconsin Alumni Foundation	Rat	7.5 and 15.0
Potatoes *	Brownell, L. E.	U. of Michigan	Rat	7.5 and 15.0
Potatoes	McCay, C. M.	Cornell U.	Dog	7.5 and 15.0
Potatoes * *	Monsen, H.	U. of Illinois	Mouse	9.3 to 11
Potatoes * *	Thompson, S.	USA MR&NL	Mouse	9.3 to 11

* Tissue Enzyme Studies also (36-week duration)

* * Carcinogenicity Study (18-month duration)

NOTE: The purpose of all studies was to determine general wholesomeness, except as indicated. Duration of feeding was approximately two years, except as noted.

Evaluations of the wholesomeness of potatoes given sprout-inhibiting doses were performed in several groups.

Cornell University investigators¹⁷ reported no unfavorable results were observed from feeding the irradiated potatoes to adult beagle dogs. All dogs were in excellent health throughout the study.

The Wisconsin Alumni Research Foundation¹⁸ reported that no harmful effects due to consumption of irradiated potatoes have been noted in parent, second, or third generation rats.

Again with rats as the experimental animal, and using the parameters of growth, food consumption, reproductive performance, hematological changes, mortality and pathological changes, the University of Michigan reported no consistent findings of differences due to consumption of irradiated potatoes¹⁹.

Irradiated potatoes were included in a mixed diet of five irradiated foods which comprised the total food intake of mice in an experiment at University of Illinois. Auricular enlargement and lesions of undetermined etiology were reported in 1959¹⁶. Efforts to reproduce and explain the phenomena by expansion of the original studies are in progress. A major part of this expanded effort is the careful duplication of all parts of the original study at the U.S. Army Medical Research and Nutritional Laboratory. This work began in mid-1960 and final results are expected in late 1962.

The gross and histopathological aspects related to studies are progressing according to schedule, and final results will be evaluated by the Armed Forces Institute of Pathology.

Human Feeding

A few of the more promising irradiated foods have been placed in the diets of human volunteers in the Metabolic Ward, Medical Research and Nutrition Lab., Fitzsimmons Army Hospital^{2, 20, 21, 23} at levels of 35, 65, 80 and 100 percent of the calories in the diet for as long as two weeks.

Of the 40 food items included in this study, all but 8 were given sterilizing doses. Those tested in the low-dose range included cabbage, sweet potatoes, white potatoes, bread, crackers, cake, strawberries, and oranges.

Complete physical examinations have been conducted periodically on the human volunteers, with follow-up examinations a year after they have been separated from the project. In order to obtain information on digestibility of such foods, complete analyses were conducted on the excreta from all participants on both the irradiated and unirradiated diets. Through all these tests, no evidence of residual toxic effects from the human consumption of irradiated food has been found^{2, 20}.

No adverse effects were observed in human volunteers on 2-week continuous diets of up to 100 percent irradiated foods; nor have there been any untoward reactions from the thousands of individuals who have sampled irradiated foods.

Considering the usual vicissitudes and difficulties characteristic of scientific work of this magnitude, considerable progress has been made. The results and public reaction on wholesomeness have progressed satisfactorily, due to the coordinated and concerted efforts directed toward this program.

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CHAPTER 9

INDUCED RADIOACTIVITY AT "PASTEURIZATION" DOSES

Induced radioactivity in food is that activity brought into being in the food during its exposure to radiation. It results from the nuclear transformation of elements in the food from an inert to a radioactive state. In considering induced radioactivity in food submitted to "pasteurization" doses, it is important to keep in mind that the energy value of the source is of primary concern. This point is elucidated in the discussion that follows.

Analytical treatment of induced-activity phenomena can be accomplished experimentally by using very low level radiation detectors and a variety of radiochemical techniques ^{1, 2, 3, 4}. The equipment and techniques used must be capable of measuring activity values equal to or less than 2 percent of standard food background (10^{-9} curies per pound) ^{5, 6, 7, 8}. The sensitivity of the measuring equipment thus places a lower limit or "zero detectability" restraint on all experimental measurements.

Theoretical values for the activity likely to be induced in food by radiation processing are also available, provided detailed information is on hand on the nature and amount of incoming radiation, the isotopic composition of the food, and the probability for each nuclear transformation event ^{9, 10, 11, 12}. No lower limit, other than the mathematical "zero", exists when a purely theoretical treatment of the induced-activity problem is followed.

Radio-process-induced activity in food is primarily an energy dependent, and secondarily, a dose-dependent phenomena. Thus, unless the radiating source has a critical energy "threshold" value, no radioactivity can in theory or practice be induced in food samples regardless of the dose delivered ^{13, 14}. At energies higher than threshold values, the amount of induced activity produced is proportional to the dose received ^{15, 16}

Stanford Research Institute and other research agencies¹⁷ have, under contract with the Quartermaster Corps, determined or verified the energy threshold values for all elements known to be or suspected of being present in foods. This work was accomplished by actual experiments and literature search; in the former case all types of radiation sources were employed.

Throughout the Quartermaster Corps studies, the dose levels given principal attention were those in the sterilization region (4 to 6 megarad), for obvious reasons. The accumulated data are directly applicable to the "pasteurization" dose work containing, as can be quickly verified, a conservative "safety factor" of 10 or more.

Repeated efforts by independent workers,^{18, 19, 20} using radiation detection devices capable of measuring concentrations as small as 10^{-14} curies per pound of sample, have failed to detect any activity in a variety of foods given 5 megarad doses in Cs^{137} , Co^{60} or X-ray sources of up to 8-Mev energy. For these sources and source energies one could not expect any induced activity at "pasteurization" doses even if the sensitivity of the detection equipment used were increased many times.

Sources using spent reactor fuel rods in a water medium cause some slight induced activity due to the mutually related factors of the high gamma energy fraction (La^{140} - 2.5-Mev), the convenient availability of unspent fissionable material remaining in the rods, and the high moderating efficiency of the water medium (H_2O)^{21, 22}. Experimental work done at such sources was done at approximately 5-megarad dose, but one would reasonably expect the induction to occur at lower dose levels. At "pasteurization" doses and below, however, detection of the induced activity would be difficult if not impossible since even at 5 megarads the activity produced is on the order of 10^{-11} curies per pound and is of relatively short half-life (Na^{24} - 15 hours).

Sources using spent reactor rods in a non-moderating (air) medium have been shown experimentally to cause no induced activity in food samples when 5 megarad doses are delivered. Radioactivity from lesser doses likewise would not be detectable²².

Electron accelerator sources, employing the electron beam directly, or the X-ray beam from an electron-bombarded target, when operated at energies of 16-Mev and above, give rise to detectable induced activity in quantities directly proportional to dose delivered. For doses of 5 megarad, an activity level of 10^{-12} curies per pound of food (beef) have been reportedly produced at 24-Mev electron energy^{23, 24}.

If, however, the electron beam or X-ray energy is kept at or below 8-Mev, all experimental evidence indicates that no detectable radio-activity will be induced in food samples sterilized by 5-megarad doses^{20, 25}.

The energy region from 8- to 16-Mev is now in the process of being thoroughly investigated by two independent agencies, since theoretical physical data show that a sizeable number of common food elements have γ -n activation thresholds in this region. As can be seen on Table 9 - 1 many of the thresholds for food component elements lie very close to the 12-Mev energy value.

It is of particular interest to note that certain applications of radiation in the "pasteurization" dose region require only shallow or "skin" doses. When electron accelerators are used to provide such skin dosing, only particle energies well below any activation threshold are needed, inasmuch as deep penetration is no longer mandatory²⁶.

TABLE 9 - 1. Threshold Energy Levels for the Production of Induced Radioactivity

Element	Type of Nuclear Change	Threshold Energy (Mev)	Half-Life of Product
Li ⁷	(γ , p)	9.8	0.85 sec
C ¹²	(γ , n)	18.7	21 min
N ¹⁴	(γ , n)	10.65	10 min
O ¹⁶	(γ , n)	16.3	2.1 min
Na ²³	(γ , n)	12.1	2.6 y
Mg ²⁴	(γ , n)	16.2	11.6 sec
Mg ²⁵	(γ , n)	11.5	14.8 h
Mg ²⁶	(γ , n)	14.0	62 sec
Al ²⁷	(γ , n)	14.0	7 sec
Si ²⁸	(γ , n)	14.8	5 sec
P ³¹	(γ , n)	12.35	25 min
S ³²	(γ , n)	14.8	3.2 sec
K ³⁹	(γ , n)	13.2	7.5 sec
Ca ⁴⁰	(γ , n)	15.9	1 sec
Fe ⁵⁴	(γ , n)	13.8	8.9 min
Mn ⁵⁵	(γ , n)	10.0	291 d
Cu ⁶³	(γ , n)	10.9	10 min
Zn ⁶⁴	(γ , n)	11.8	38.3 m
Cu ⁶⁵	(γ , n)	10.2	12.8 h
Zn ⁶⁶	(γ , n)	11.6	245 d
Br ⁸¹	(γ , n)	10.7	6.4 min
I ¹²⁷	(γ , n)	9.3	13 days

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CHAPTER 10

DOSIMETRY AND DOSE DISTRIBUTION

Dosimetry — the measurement of radiation dose at a point in space — and dose distribution — the dose measurements throughout food sample volumes — are as important to low-dose "pasteurization" of foods as to high-dose sterilization of these items.

At the outset of the radiation preservation of food program in 1953, very little was known about high-intensity dose measurement, and ultimate proven dose ranges could not be accurately predicted for the various processing methods, such as (1) inhibition of sprouting; (2) inactivation of trichina; (3) insect disinfestation; (4) "pasteurization" of foods; (5) sterilization of foods; and (6) enzyme inactivation. Initial dosimetry and dose distribution efforts were therefore directed toward finding measuring devices and formulating techniques capable of being used in all dose range applications.

The research and development tasks associated with dosimetry and dose distribution proved to be among the most difficult and challenging in the food radiation program due to the following complicating factors:

- a. Wide range of dose requirements (10^4 to 10^7 rad).
- b. Wide range of radiation energies:
0.3 - 3.0 Mev or higher for gamma - X-rays
1.0 - 50.0 Mev for electrons
- c. Variable dose rates required
to 10^7 rad/hr for gamma - X-rays
to 5×10^8 rad/min for electrons
- d. The scattered geographical locations, and considerable variations in source geometry and routine dosimetry techniques preferred by source operators (see Table 10-1).

TABLE 10-1. Factors Affecting Dosimetry and Dose Distribution

Sources of Radiation	Locations	Kinds of Radiation	Systems of Routine Dosimetry
Materials Testing Reactor spent fuel elements (in H ₂ O)	National Reactor Test Station, Idaho	.75 Mev Gamma ^a	Ceric Sulfate Ion Chamber
" " " (in air)	Dugway Proving Ground, Utah	" " "	Ceric Sulfate
" " " (in H ₂ O)	Argonne National Lab., Ill.	" " "	Ferrous Sulfate
Savannah River spent fuel elements (in H ₂ O)	Savannah River Plant, So. Car.	" " "	Ceric Sulfate Ion Chamber
Cesium-137	Georgia Inst. of Tech., Atlanta, Georgia	.66 Mev Gamma	Ceric Sulfate
Cobalt-60	Dugway Proving Ground, Utah	1.17 and 1.33 Mev Gamma	Ceric Sulfate
" " "	Cook Elec. Labs. Ill.	" " "	Ferrous Sulfate Ion Chamber
" " "	Stanford Res. Inst. Calif.	" " "	Ferrous, Ceric Sulfate Calorimetry
" " "	Argonne National Lab. Ill.	" " "	Ion Chamber
" " "	Univ. of Michigan, Michigan	" " "	Ferrous Sulfate Cupric Sulfate
Van de Graaff accelerator	High Volt. Eng. Corp., Mass.	D.C. Electron Beam	Beam Current Monitor
Resonant transformer	Gen. Elec. Corp. Wis.	Pulsed Electron Beam	" "
" " "	Mich. St. Univ. Mich.	" " "	" "
" " "	Stanford Res. Inst., Calif.	" " "	" "
Linear electron accelerator	Applied Rad. Corp., Calif.	" " "	" "
" " "	Midwest Irrad. Center, Ill.	" " "	" "
" " "	Stanford Univ. Calif.	" " "	" "
" " "	Argonne Cancer Res. Hosp., Ill.	" " "	" "
" " "	Michael Reese Hosp. Ill.	" " "	" "
" " "	General Atomics Corp., Calif.	" " "	" "
^a . Mixed Mev Average			

The prime function of a dosimetry system is to ascertain that an accurate and precise dose is delivered to the food sample. To accomplish this, it was foreseen that three general categories of dose measuring devices would be required. These functional types are:

- a. A "primary standard" national dosimeter, against which all other dosimeters used in the program could be checked and calibrated.
- b. A secondary dosimetry system, serving as the basic standard for a particular source geometry, and specifically suited for the operating conditions of that source.
- c. A simple, inexpensive, easy-to-read "Go-No-Go" dosimeter which could be affixed to each sample during irradiation to guarantee that the sample received no less than a critical minimum and no more than a limiting maximum dose.

To develop a dosimetry capability for fulfilling these requirements, efforts were directed toward:

- a. Conducting an aggressive research program including internal, contractual, and working-agreements;
- b. Seeking assistance from the National Research Council and other National Committees in the testing and standards fields;
- c. Stimulating exchanges of scientific data on dosimetry development;
- d. Obtaining proven dosimetry systems as they became available.

The use of generally-accepted standards has eliminated much of the earlier discrepancies in results reported from various laboratories. Secondary dosimetry systems have been developed, using Cobalt glass for the lower dose ranges, and ceric sulfate for the megarad range. Also, an expendable "Go-No-Go" device, utilizing a polymerization-gelation system has been developed for positive identification of dosages between predesignated narrow limits.

An integrated family of dosimetry systems, which the Quartermaster Corps has developed through research and adaptation, is presented in Table 10-2. Detailed procedures for preparation, use, and evaluation of these systems are available, upon specific request to the U. S. Army Quartermaster Food and Container Institute for the Armed Forces, Chicago, Ill.

TABLE 10-2. DOSIMETRY SYSTEMS PRESENTLY BEING USED BY THE QUARTERMASTER CORPS FOR

DOSIMETRY SYSTEM-PRINCIPLE	USABLE DOSE RANGE IN RADS	PRECISION IN %	APPLICATION	ADVANTAGES
Fricke (Ferrous-Ferric) Oxid.	5×10^3 - 7×10^4	± 1	Most widely used and most reliable dosimeter - QMC secondary dosimeter used for source calibration, to calibrate Ceric, Cobalt Glass, Radipol and Blue Cellophane	High accuracy analysis without treatment, occupy space of sample.
Ceric Sulfate Reduction of Ceric to Cerous	10^5 - 10^8	± 2	In sterilization dose range, long-time exposure calibrations to eliminate time variable. Dose distribution measurements.	High-Dose Accuracy
Bausch & Lomb Cobalt Glass F-0621 Change in Optical Density	5×10^3 - 2×10^6	± 2	"Pasteurization" Dose Range. Dose Distribution Measurements.	Simplicity, Ruggedness
Blue Cellophane DuPont 300 MSC Optical Change in Transmission	10^4 - 10^7	$\pm 2\%$ with moisture controlled. ± 10 non-controlled	Dose Distribution (white skin)	Convenience, Simplicity
Radipol (Hoecker) Polymerization of Polyesters	10^3 - 10^7	± 5	"Pasteurization" and Sterilization. Dose range, calibration, dose distribution and quality control (Go-No-Go)	Wide Dose Range No auxiliary equipment and technique
Calimetry Measure Heat Rise	5×10^3 - 5×10^7	± 2	As absolute standard	Absolute
QMC Secondary Emission Current Monitor	10^5 - 5×10^8	± 4	Determine constancy of accelerator operation. Not a dosimeter but rather a beam measuring device for electron only; signal must be correlated to absorbed dose.	Correlates with dose at acceleration window with the on control
QMC Stacked Beam-Foil Energy Method	10^5 - 5×10^8	± 10	Measure electron energy of accelerator.	Energy monitor for stationary beam
Monitors Emmis. Cham. Method	10^5 - 5×10^8	± 10	Measure electron energy of accelerator.	Energy monitor for scanned beam
QMC Ionization Chambers	5×10^4 - 10^7	± 10	Determine Gamma-Dose Rates	Direct readout ability of readout unlimited scale

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APPLICATION	ADVANTAGES	DISADVANTAGES	REFER- ENCES
Most widely used and most reliable dosimeter - QMC secondary dosimeter used for source calibration, to calibrate Ceric, Cobalt Glass, Fadipol and Blue Cellophane	High accuracy, direct analysis without further treatment, solution can occupy space and volume of sample.	Need for operator experience, care in irradiation and auxiliary equipment. Low-Dose Range	1, 2, 3
In sterilization dose range, long-time exposure calibrations to eliminate time variable. Dose distribution measurements.	High-Dose Range, High Accuracy	Need for operator experience. Auxiliary equipment including titrator at high doses. Detailed in preparing solution.	1, 2, 4, 5, 6, 7
"Pasteurization" Dose Range. Dose Distribution Measurements.	Simplicity, Accuracy, Ruggedness	Need for calibration, limited dose range. High Atomic Number Composition.	1, 19, 20
Dose Distribution (micro skin)	Convenience, Cost Simplicity	Variation of accuracy with different batches, moisture control	9, 10, 11, 12, 13
"Pasteurization" and Sterilization. Dose range, calibration, dose distribution and quality control (Go-No-Go)	Wide Dose Range, Cost, No auxiliary equipment and technical personnel	Decrease of sharpness of index at highest doses. Refrigeration needed for storage	16, 17, 18
As absolute standard	Absolute	Suitable for standardization only, need for highly skilled personnel	1
Determine constancy of accelerator operation. Not a dosimeter but rather a beam measuring device for electron only; signal must be correlated to absorbed dose.	Correlates beam current at accelerator exit window with that registered on control panel	Supporting vacuum equipment, slight interference with beam	1
Measure electron energy of accelerator.	Energy monitor for stationary beam.	Cannot be used with some beam scanning and deflection-magnet systems	1
Measure electron energy of accelerator.	Energy monitor for scanned beam	Samples beam only small fraction of time	1
Determine Gamma-Dose Rates	Direct reading, availability of recycling, unlimited shelf-life	Low Accuracy, Up-Keep High	8



The spatial distribution of absorbed dose, i. e., the distribution of the energy absorbed from the radiation field per unit mass of food is equally as important to the food processor as an accurate system of dosimetry. Inasmuch as the uniformity of food treatment is dependent upon the distribution, it is essential that it be completely uniform. Absolute or complete uniformity cannot, however, be attained in practice²⁴, because the energy-absorption process, upon which the radiation treatment depends, causes intensity of the radiation field to vary throughout the food. The problem then becomes one of developing irradiation and measurement techniques that can produce the most uniform dose distribution in a food package.

Distribution can be measured by inserting small dose sensors at various points in the food samples prior to processing and then withdrawing, and analyzing these monitors. However, more advanced methods are needed, both from an operational and product quality control standpoint.

A more realistic solution is to measure the radiation parameters, such as energy, current, and dose rate which can be related to absorbed dose.

The relationship between these parameters and absorbed dose is established by means of dosimetric test packages, throughout which are distributed a number of dosimeters. These test packages, or phantoms, are constructed to simulate, as closely as possible, energy absorption characteristics of the various types of production packages^{11, 12, 21, 22, 23}. These phantoms are then irradiated using the same parameter values, radioisotope (or beam energy and beam current), dose rate and conveyor speed that will be used during the production process. For additional assurance of satisfactory operations, test packages are interspersed periodically in the production run.

To achieve the desired biological effect with adequate wholesomeness, The Quartermaster Corps has established that the radiation energy received by a sample at any point should be within the limits of 100-115 percent of the prescribed dose. Figure 10-1 illustrates the dose variation in a number 2 can irradiated unidirectionally with 1.25-Mev, Cobalt-60 gamma rays, 10-Mev electrons, or 10-Mev X-rays²⁵.

UNIDIRECTIONAL RADIATION DOSE - DEPTH CURVES

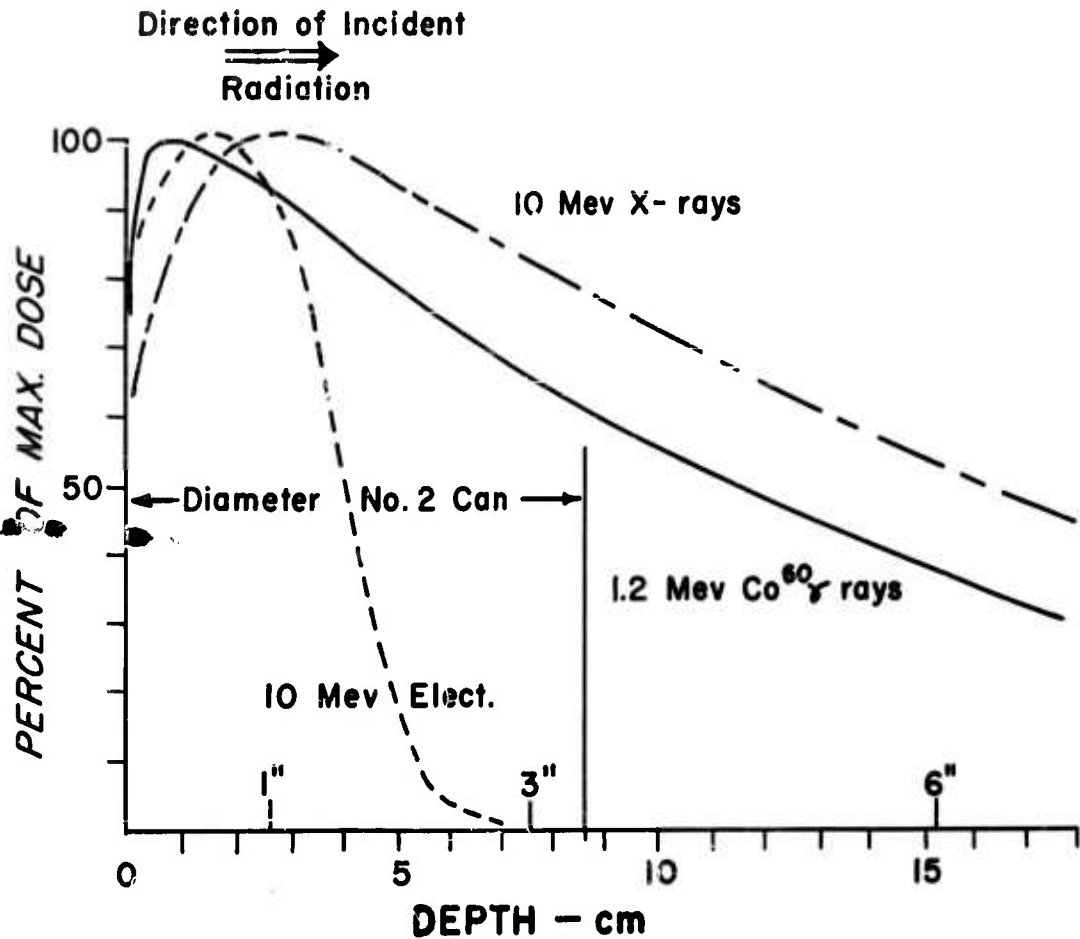


Figure 10-1. Dosimetry tests showed that dose variations in a No. 2 can, irradiated unidirectionally, were within the prescribed limits of 100-115 percent.

To decrease dose variation, techniques such as bidirectional radiation as illustrated in Table 10-2 have been used. Further uniformity is achieved by the use of absorbers and scatterers placed on the top, bottom, and sides of the food packages.

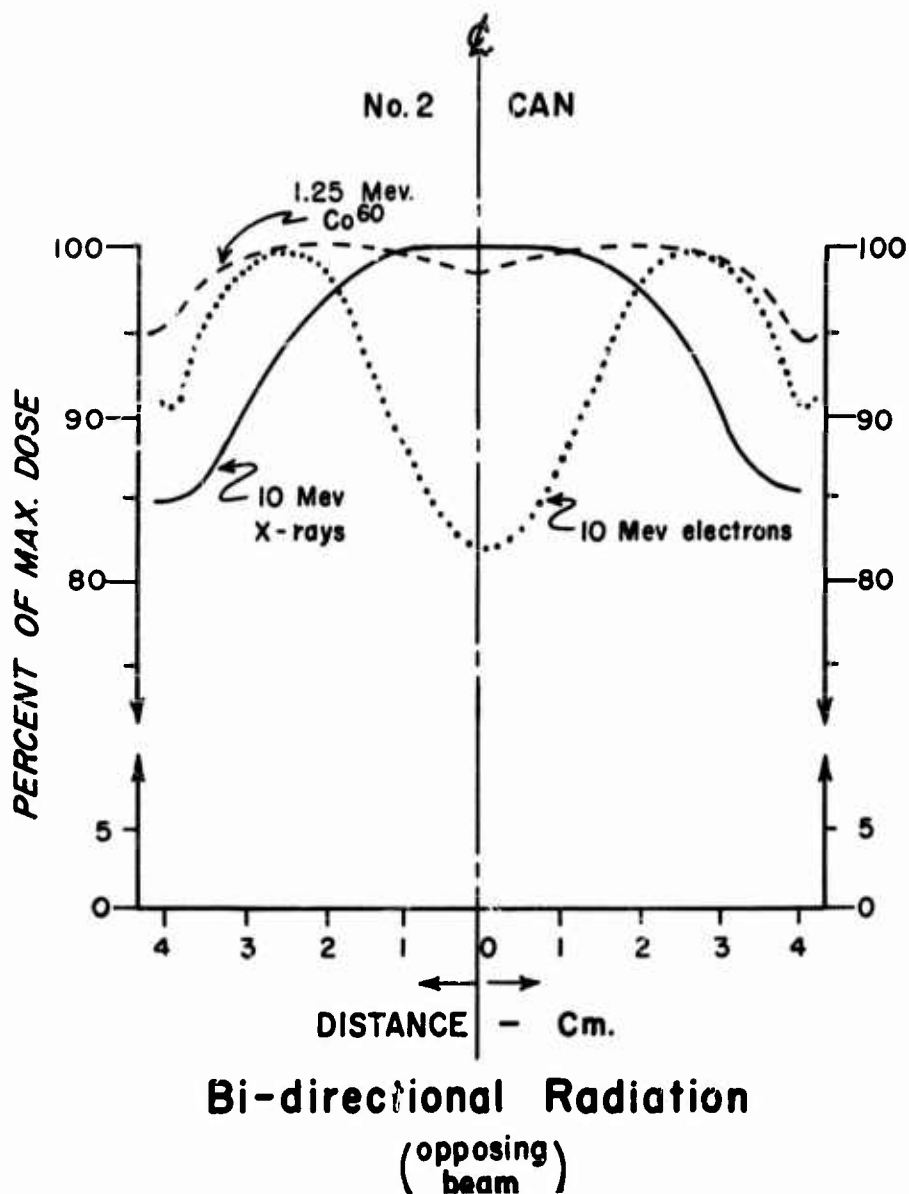


Figure 10-2. Effects of Bidirectional Radiation in Decreasing Dose Variations are shown by dotted line. This technique increases uniformity of dose distribution.

Experimental studies of the dose distribution as a function of select process variables such as radiation energy, sample composition, and container configuration are necessary for all samples. Such studies are particularly essential for dosimetric coverage of fresh fruits and vegetables. Good dose distribution in containers for these items requires special consideration due to the air space in these package volumes.

Special experimental dosimetric effort is also needed and underway^{14, 15} to investigate heterogeneous sample systems and secondary electron doses at container - food boundaries. Analytical analyses of such studies which are currently being conducted will provide information vital to achieving adequate dose and dose distribution, particularly in specialized "pasteurization" processing techniques, such as surface treatment, and lug-size sample irradiations.

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CHAPTER 11

PACKAGING FOR LOW-DOSE IRRADIATED FOODS

Packaging for foods treated with low doses of radiation (one megarad or less) does not pose as many serious problems as packaging for foods sterilized by high-dose radiation. Where packaging problems presently exist with low-dose irradiated foods, the problems are less severe and hold promise of satisfactory solution in the near future.

Influence of Radiation on the Package

Numerous investigations confirm the statement that, in general, packaging is not affected by low doses of radiation. At doses of one megarad or less the effect on the physical properties of packaging materials (tensile strength, elongation, moisture, vapor transmission rate) is small and the finished package is not affected^{2, 6, 7, 8, 9, 12}. It is true that gaseous products are released at these doses and that they contribute to off-flavors and unnatural odors^{3, 11, 13}. However, the flavor score of products such as corn, green beans, and strawberries is not affected⁴. Other products - bland items and items normally sensitive to the absorption of flavors - may be affected by some packaging materials; however, selection of proper material can preclude this problem^{10, 11}. For example, bread irradiated at 50,000 rad in polymer-coated cellophane acquired an acrid flavor, whereas bread in normal-type cellophane was unaffected¹³. Although it is not possible to rank all packaging materials in the order of increasing odor development, polyethylene is high on the list of materials in which odor development is of concern.

Recently, an additive has been found⁵ which is effective in reducing odors and extractives in irradiated polyethylene. If future work bears out current results, this additive will virtually eliminate the problem. No doubt, its use can be extended to other polymers.

Stress-crack resistance of plastics is improved by sterilizing doses of irradiation^{1, 2, 8}, but is not affected by low-dose treatments. However, since this characteristic is temperature sensitive, stress-cracking will not be encountered with refrigerated products. Moreover, even in cases where the low-dose treated foods are stored at ambient

temperatures, it is possible to select packages which will avoid this problem.

Application of Packages to Foods

Studies on the packaging of low-dose irradiated foods have revealed some interesting facts. Irradiated cooked foods require that air be excluded from the package. On the other hand, packaged irradiated "fresh" foods require that air be present for respiration. Furthermore, the problem is accentuated by the fact that different foods require air in varying amounts. Fresh fruits and vegetables, for instance, require more air to remain in a sound healthy condition than fresh meats. These factors require that two types of packages be utilized: (1) completely sealed packages for cooked irradiated foods, and (2) perforated or incompletely sealed packages for irradiated fresh fruits and vegetables, and for tuberous foods. Table 11 - 1 lists packaging which is satisfactory for a variety of food items.

Packaging Problem Areas

The respiration requirements for packaged irradiated foods are a major problem. The present practice of using perforated and incompletely sealed packages for irradiated fresh fruits and vegetables is undesirable because packaging of this type will permit some recontamination by microorganisms. The first step in solving this problem is to determine the optimum air requirements of each food, i. e. , finding the air level at which the minimum requirements of a food are met. The next step is to apply packaging consonant with the air needs. The packaging must, in addition, prevent the recontamination of the product. Thus, a two-fold approach to improving the shelf-life of perishable foods is required: (1) radiation to reduce the microbial population, and (2) a package which will control the respiration at the proper level, and thereby retard the rate of natural deterioration of the perishable item.

TABLE 11 - 1. Packages for Foods Treated with Low-Dose Radiation

Type of Product	Condition		Package Requirement	
			Refrigerated Storage	Ambient Temperature Storage
Meat	Raw	Carcass	Waxed-kraft bags, parchmentized kraft bags, pliofilm bags	Same as refrigerated.
		Large cuts		
	Cured	Individual cuts	Cellophane, pliofilm, polyethylene, polystyrene, and similar containers presently used.	Packages with low moisture rates, i.e., polyethylene-coated Mylar, cellophane, Saran; carefully selected grades with stress-crack resistance
			Packages which minimize oxygen and moisture transfer, i.e., Saran, pliofilm, vinyl; polyethylene-coated Mylar or cellophane.	Same as refrigerated. Care must be taken to select grades with stress-crack resistance.
	Cooked		Packages which minimize oxygen and moisture transfer. Polyethylene-coated cellophane or Mylar, Saran, Saran-pliofilm, etc.	Same as refrigerated. Care must be taken to select grades with stress-crack resistance.
Fruits and Vegetables	Fresh		Present type packages are satisfactory (perforated bags, where required).	Same as refrigerated.
	Enzyme inactivated or cooked		Packages which minimize oxygen and moisture transfer, i.e., polyethylene-coated cellophane or Mylar, Saran, etc.	Same as refrigerated. Care must be taken to select grades with stress-crack resistance.
Tubers	Sprout inhibition		Present type of containers are satisfactory	Same as refrigerated.
	Insect control (i.e., nematodes)		Crates with paper liners, multiwall paper sacks and other containers without opening which will allow respiration are satisfactory	Same as refrigerated.
Cereal grains				Multiwall paper sacks treated with pyrethrin-piperonyl butoxide.

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PART V

ECONOMICS OF LOW-DOSE RADIATION PROCESSING

Verified cost analyses for processing foods by ionizing radiation are not available inasmuch as production facilities from which to obtain such data do not exist. However, many estimates of future production costs have been made, particularly by the principal manufacturers of electron generators. The calculations for processing by electron sources are more complete than those for gamma radiation, due primarily to the lack of firm prices for the use of nuclide-produced radiation. Another contributing factor is the unavailability of realistic cost data for nuclear reactors, inasmuch as to date no reactors have been constructed to optimize the production of gamma radiation.

Because of this paucity of practical data, it is difficult to evaluate critically cost estimates advanced for radiation processing. This review, based largely upon the estimates presented by leading manufacturers, should provide a fair appraisal of the magnitude of processing costs associated with the various types of electron and gamma sources proposed for use in the preservation of foods by low-dose ionizing energy.

The data presented in this review develops the cost factors for the respective radiation sources, and also combines these factors to formulate estimated production costs, expressed on a per kilowatt-hour (kwh) basis. Where appropriate, points of comparison are drawn between electron and gamma sources. Consideration has been given to potential reduction in any of the cost factors which can be reasonably estimated for the 1965-1970 time frame. It must be stressed, however, that production costs developed in this review are directly related to particular applications and, therefore, should not be used out of context. The major cost factors to be considered are:

- (1) Initial acquisition cost of radiation source.
- (2) Installation cost, including building space, primary shielding, cooling and ventilating equipment, and ancillary facilities.
- (3) Transportation cost, based on 1000 miles.
- (4) Operational and maintenance costs, including direct labor; overhead, power-source replacement, or source replenishment; maintenance; miscellaneous parts and utilities.

CHAPTER 12

IONIZING ENERGY SOURCES

For all practical purposes, only two general sources of radiation (1) high energy electron generators, and (2) gamma radiation from radio isotopes, need be considered for the time frame under study. X-radiation obtained from the conversion of the electron beam need not be considered inasmuch as the efficiency of converting electron beam power to X-ray power is so very low, at the lower energy level. If high energy electrons are used to obtain acceptable conversion efficiency, the X-rays are highly penetrating and cannot be utilized for processing as efficiently as the electron beam for a given production capacity. The power cost for X-ray processing would be significantly increased as well as the initial cost of the radiation cell. Thus, X-ray tubes have been eliminated from this review as a potential competitive source for low-dose radiation.

In considering electron sources, cost factors representative of existing technology have been utilized. In the case of nuclide sources, however, the cost factors used, while based on existing technology, are of necessity keyed to production levels many times the curie strength currently in use, and hence to a technology yet unexplored. In the case of both types of sources, however, the cost factors reflect conditions that should exist when large-scale radiation becomes operational in industry rather than on the basis of current circumstances wherein only a few applications have been established.

The following assumptions have been employed in formulating the cost factors which in all cases are presented in terms of dollars per kwh:

(1) Ten-year straight line depreciation of the radiation sources, and installation.

(2) Earnings at 10% per annum after taxes on total capital invested during ten-year depreciation period.

(3) Three-shift operation (6,000 hours per year).

The above assumptions represent only some of the parameters which must be considered in the economic evaluation of radiation processing. The following variables, although exempt from consideration in this review, are recognized as significant factors in any given application of low-dose radiation processing:

- (1) The efficiency of radiation utilization -- percentage of radiation delivered by the source that is usefully absorbed in the product.
- (2) The through-put -- pounds per hour being processed.
- (3) Dependability of operation -- percentage of downtime.
- (4) The conveying system complex.
- (5) Other ancillary equipment.

A review of the preceding variables should indicate the desirability of excluding these items from this review inasmuch as each radiation source and commodity being treated possesses its own problems and considerations. In every case, however, the pounds which can be processed per hour at any given dose level, can be directly related to the kilowatt (kw) output of the radiation source. Once the power output and utilization efficiency have been defined, the pounds per hour, as a function of dosage, can be determined from the following table :

TABLE 12 - 1. Output as a Function of Dosage and Utilization Efficiency

Efficiency, (%)	Pounds per hour per kw output		
	Dosage in Megarad		
	.01	.1	1.
100	8,928	8,928	893
90	80,445	8,045	804
80	71,424	7,142	714
70	62,496	6,250	625
60	53,475	5,348	535
50	44,640	4,464	446
40	35,712	3,571	357
30	26,784	2,678	268
20	17,856	1,786	179
10	8,928	893	89

Factors upon which to base a comparative analysis between electron accelerators and nuclide power sources are presented in the following sections:

1. ELECTRON ACCELERATORS

As early as 1954, The High Voltage Engineering Company, one of the pioneer firms in the field of electron generators, envisioned production costs of a dollar per kwh for electron processing of food¹. This estimate was made when the actual costs were in the order of magnitude of \$3.00 to \$20.00 per kwh. The General Electric Company in 1956 also estimated the future cost of electron power to approach \$1.00 per kwh². It is of interest to note that as recently as January 1960 this figure has been further substantiated by the Applied Radiation Corporation in developing cost estimates for operating their existing 5-kwh L-band linear accelerator. Their estimate without considering the return on the initial capital investment is \$0.95 per kwh³.

The principal types of machines currently available for processing foods by low-dose ionization energy are summarized as follows:

TABLE 12 - 2. Machinery and Performance Characteristics

<u>Machine</u>	<u>Current Performance Characteristics</u>		<u>Future Performance Characteristics</u>	
	<u>Kw</u>	<u>Mev</u>	<u>Kw</u>	<u>Mev</u>
Van de Graaff Generator	1-5	1-4	No significant change	
Resonant Transformer	5-25	1-4	No significant change	
Linear Accelerator	1-20	3-30	1-500	3-30
Dynamitron	15	1 1/2	45	3

Initial Cost of Acquisition and Installation

The following cost values have been selected and compiled for purposes of this review after analyzing the purchase-price data currently published, quoted, or estimated by manufacturers. The cost data selected for installation includes the cost of building space, primary shielding, cooling and

ventilating equipment, and the cost of ancillary facilities:

TABLE 12 - 3. Estimated Acquisition and Installation Costs

<u>Machine Rating</u>		<u>Purchase Price</u>	<u>Installation Cost</u>
<u>Kw</u>	<u>Mev</u>	<u>(\$ per Kw)</u>	<u>(\$ per Kw)</u>
3	1.5-3	\$22,000	\$15,000
5	1.5-8	34,000	10,000
30	1.5-3	10,000	3,000
60	12-20	6,000	2,500

Although the installation cost figures may appear to be higher than some previously published, they are considered to be in the best interest of flexible and conservative estimation.

Cost of Transportation

Accumulated experience in the shipment of electron-magnetic equipment of this type indicates a figure of \$150 per kw of radiation capacity per 1000 miles.⁴ For the sake of uniformity, 1,000 miles have been used in all cost evaluations.

Cost of Maintenance and Operation

Estimated operating and maintenance costs for the electron generators under consideration have been summarized in Table 12 - 4.

TABLE 12 - 4. Estimated Operating and Maintenance Cost for Radiation Machine Installations^a

<u>Item</u>	<u>3-kw</u>	<u>5-kw</u>	<u>30-kw</u>	<u>60-kw</u>
1. Direct Labor at \$3.00 per Man-Hour	\$36,000/yr ^b	\$36,000/yr ^b	\$54,000/yr ^c	\$72,000/yr ^d
2. Overhead at 100%	36,000/yr	36,000/yr	54,000/yr	72,000/yr
3. Power-Source Re- placement (tube or other)	24,000/yr ^e	30,000/yr ^f	36,000/yr ^g	72,000/yr ^h
4. Miscellaneous Parts and Utilities	6,700/yr	7,200/yr	14,500/yr	29,000/yr
5. Total Annual Opera- ting and Maintenance Cost	102,700/yr	109,200/yr	158,500/yr	245,000/yr
6. Operating and Main- tenance Cost per Kilowatt-hour Prod- uced	\$5.70/kwh	\$3.65/kwh	\$0.90/kwh	\$0.70/kwh

a. Based on an operating schedule of 6,000 hours per year, 3 shifts.

b. Assumes two equivalent full-time personnel to perform operating, main-
tenance, and health-physics functions.

c. Assumes three equivalent full-time personnel to perform operating, main-
tenance, and health-physics functions.

d. Assumes four equivalent full-time personnel to perform operating, main-
tenance, and health-physics functions.

e. Assumes cost of \$4 per hour of operation.

f. Assumes cost of \$5 per hour of operation.

g. Assumes cost of \$6 per hour of operation per machine.

h. Assumes cost of \$12 per hour of operation per machine.

Summary of Cost for Electron Radiation Sources

Table 12 - 5 summarizes the foregoing cost factors and develops an estimated cost figure in terms of dollars per kwh.

Visualizing the future potential of electron generators, it would appear that the cost of the radiation sources may be reduced by as much as 50% on the purchase price of machines of low to moderate power.

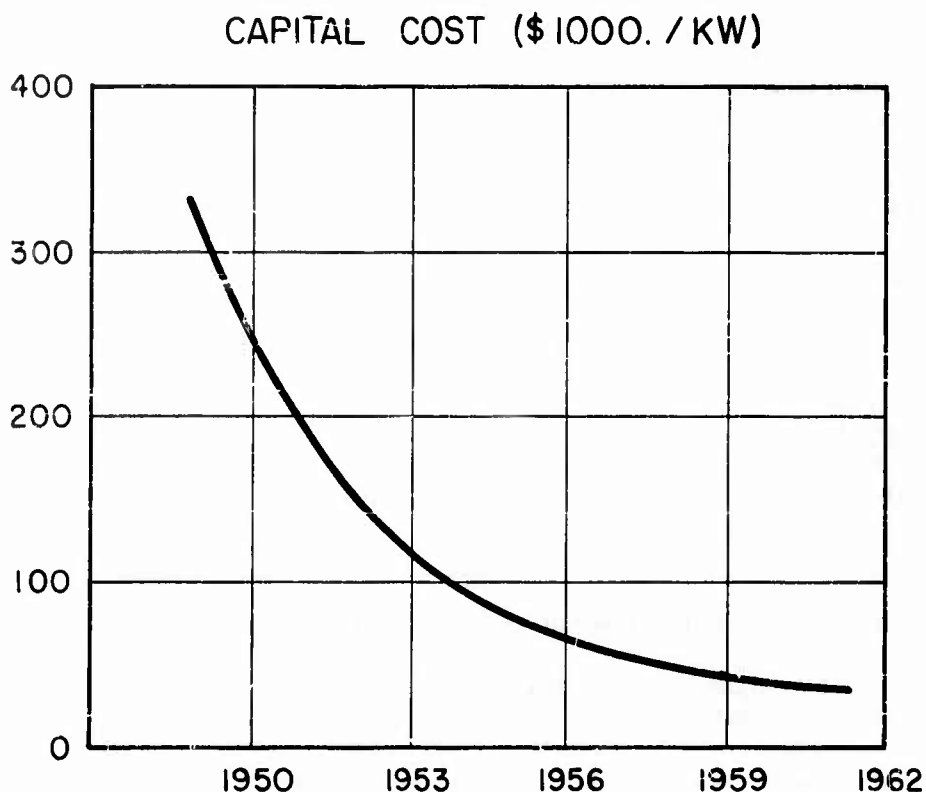


Figure 12 - 1. Trend of capital costs for electron accelerators.

This declining trend in capital costs for electron accelerators which has existed over the past decade indicates a possible 50% purchase price reduction. In the case of the 30-kw application presented in Table 12 - 3, this would reduce the estimated radiation production cost from \$1.30 per kwh to the \$1.00 per kwh which has been adopted by the majority of accelerator manufacturers as the goal for the 1965-1970 time frame.

TABLE 12 - 5. SUMMARY COST ANALYSIS OF RADIATION MA

Item	3-kw	5-kw	30-kw
1. Purchase price of machines(s)	\$ 66,000	\$170,000	\$300,000
2. Shipment (1000 miles)	450	750	4,500
3. Installation	<u>45,000</u>	<u>50,000</u>	<u>90,000</u>
4. Total capital investment	\$111,450	\$220,750	\$394,500
5. Depreciation (10-year straight-line)	\$ 11,145/yr	\$22,075/yr	
6. Operation and maintenance (see Table 12-4)	102,700/yr	109,200/yr	
7. Total annual cost <u>excluding</u> return on investment	113,845/yr	131,275/yr	
8. Cost per kilowatt-hour produced, <u>excluding</u> return on investment	\$6.35/kwh	\$4.40/kwh	
9. Provision for return on investment (at 10% annum after taxes)	11,145/yr	22,075/yr	
10. Total annual cost <u>including</u> return on investment ^a	124,990/yr	153,350/yr	
11. Cost per kilowatt-hour produced, <u>including</u> return on investment	\$6.95/kwh	\$5.10/kwh	

a. Based on an operating schedule of 6,000 hours per year.

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TABLE 12 - 5. SUMMARY COST ANALYSIS OF RADIATION MACHINES^a

	3-kw	5-kw	30-kw	60-kw
(s)	\$ 66,000	\$170,000	\$300,000	\$360,000
	450	750	4,500	9,000
	<u>45,000</u>	<u>50,000</u>	<u>90,000</u>	<u>150,000</u>
	\$111,450	\$220,750	\$394,500	\$519,000
ht-line)	\$ 11,145/yr	\$22,075/yr	\$39,450/yr	\$ 51,900/yr
see Table	102,700/yr	109,250/yr	154,500/yr	245,000/yr
return	113,845/yr	131,275/yr	197,950/yr	286,900/yr
ced, ent	\$6.35/kwh	\$4.40/kwh	\$1.10/kwh	\$0.80/kwh
stment	11,145/yr	22,075/yr	39,450/yr	51,900/yr
turn	124,990/yr	153,350/yr	237,400/yr	348,800/yr
ed, t	\$6.95/kwh	\$5.10/kwh	\$1.30/kwh	\$1.00/kwh

e of 6,000 hours per year.

A significant development in linear accelerators, unveiled by Applied Radiation Corp. in September 1959, was the L-band accelerator. This company has estimated that the L-band accelerator may eventually bring the cost of producing radiation power down to about one-quarter of its current level, which would place it well within the realm of the dollar per kwh figure³.

Radiation Dynamics Inc. has developed, and is now manufacturing, a new line of accelerators known as Dynamitron. This unit is characterized by its relatively large current output, rugged construction and consequent industrial reliability, and low cost per kw of output. Radiation Dynamics now estimates three-shift operations in the order of \$.80 per kwh⁵. There are no apparent difficulties in increasing beam current in the Dynamitron, and the second generation of Dynamitrons at power levels of 100-kw are already anticipated. Inasmuch as it is obvious that the cost per kilowatt hour will further decrease as power increases, this firm has estimated costs of 10-25¢/per kwh.

2. NUCLIDE SOURCES

The three principal types of nuclide sources for preserving food by low-dose ionizing energy which can be made available during the time frame under consideration are:

(1) Cobalt 60 (Co-60), produced by the irradiation of cobalt in nuclear reactors.

(2) Cesium 137 (Cs-137), a fission product recovered from radioactive effluent from spent-fuel rods.

(3) Zirconium-niobium mixtures (ZirNob), a semi-refined mixed fission product separated from spent-fuel reprocessing operations.

Several facilities employing Co-60 sources, ranging in strength from 10,000 to 100,000 curies are now in use. The U. S. Army's Quartermaster Radiation Laboratory, to be constructed at the Quartermaster Research and Engineering Center, Natick, Massachusetts, will employ a Co-60 source of approximately 1-million curies.

A pilot plant now exists for the recovery of Cs-137 from spent-fuel reprocessing operations at the Atomic Energy Commission's Oak Ridge National Laboratory; however, the current production rate is only 200,000 curies per year. As for ZirNob sources, they are not currently available but their potential is receiving careful consideration. ZirNob has a very short half-life, requires frequent replacement, and thus, has a relatively high operating cost. On the other hand, it is considerably cheaper to produce than the separated fission products, such as cesium, and thus represents a much lower capital investment.

Initial Cost of Acquisition

The source strengths considered in this review have led to the following curie requirements:

TABLE 12 - 6. Curie Requirements^a

<u>Source Size</u>	<u>Cobalt-60</u>	<u>Cesium-137</u>	<u>ZirNob</u>
3-kw	252, 000	1, 216, 000	908, 000
5-kw	420, 000	2, 027, 000	1, 513, 300
30-kw	2, 520, 000	12, 160, 000	9, 080, 000
60-kw	5, 040, 000	24, 320, 000	18, 160, 000

a. These requirements allow for self-absorption energy loss of 10, 15, and 15 percent for Co-60, Cs-137, and ZirNob, respectively. In addition to self-absorption, these requirements also allow for sufficient over-design (approximately 10 percent) to assure rated capacity at the end of any given replacement period.

In keeping with the premise of looking to the future in developing costs, the following price estimates have been established:

TABLE 12-7. Cost Estimates for Processing with Nuclear Sources

<u>Source Size</u>	<u>Nuclide Price (\$/Curie)</u>		<u>ZirNob</u>
	<u>Colbat-60</u>	<u>Cesium-137</u>	
3-kw	\$0. 75	\$0. 25	\$0. 04
5-kw	0. 75	0. 25	0. 04
30-kw	0. 50	0. 15	0. 02
60-kw	0. 40	0. 12	0. 02

Cost of Installation

The remarks previously made relative to conservatism in estimating the cost of installing electron generators also apply to nuclide sources. The values utilized in this review are as follows:

TABLE 12 - 8. Cost of Installation

<u>Source Size</u>	<u>Cobalt-60</u>	<u>Cesium-137</u>	<u>ZirNob</u>
3-kw	\$120, 000	\$120, 000	\$120, 000
5-kw	200, 000	200, 000	200, 000
30-kw	300, 000	300, 000	300, 000
60-kw	480, 000	480, 000	480, 000

Cost of Nuclide Source Preparation

While there is yet no factual experience in preparing megacurie sources, indications are that cost of 5 cents per curie for Co-60 and 10 cents for Cs-137 are feasible.⁴ These figures have been employed for the entire range of source sizes in this report. The figures used for ZirNob do not specify a specific source preparation charge since the nuclide price, expressed in dollar per curie, includes source preparation and allowances for the cost of transportation and disposal.

Cost of Transportation

Information developed by the Atomic Energy Commission indicates a cost of 1 cent per curie per 1000 miles for transportation of Co-60 and Cs-137 sources based on maximum of 100,000 curies per shipment.⁴ No specific charge is indicated for ZirNob because the nuclide price estimate, expressed in dollars per curie, includes allowances for cost of transportation and disposal. For the sake of uniformity a 1000-mile shipping distance has been used in all cost evaluations. This figure includes freight charges, use of shipping containers, insurance and carrier burden.

Replacement Costs

Replacement requirements have been calculated on the basis of maintaining source strength at a minimum of 90 percent of the initial strength which will assure a 100 percent of the designed rating at this point. Cobalt-60 decays to 90 percent of its original strength in 292 days, Cesium-137 in approximately 1,660 days, and ZirNob in 11 years. It has been assumed for the

purpose of this review that the source will be divided into many elements, any of which may be replaced to maintain the desired strength. On this basis the following annual replacement schedule to maintain 90 percent of the original strength has been developed:

Cobalt-60	12.5%/yr
Cesium-137	2.2%/yr
ZirNob	330%/yr

Using percent-required replacement rates, and employing the per curie cost, plus the preparation and transportation costs, the following replacement charges have been developed:

TABLE 12 - 9. Estimated Replacement Costs

<u>Source Size</u>	<u>Cobalt-60</u>	<u>Cesium-137</u>	<u>ZirNob</u>
3-kw	\$23,900	\$ 9,500	\$120,000
5-kw	43,000	19,000	160,000
30-kw	176,000	68,500	600,000
60-kw	290,000	124,000	1,200,000

Cost of Maintenance and Operation

The estimated operating and maintenance costs for nuclide sources have been summarized in Table 12 - 10. The dollars per kwh may appear somewhat higher than values previously published; however, as in the case of electron machines, conservative figures have been used for the sake of flexibility and unforeseen contingencies.

TABLE 12 - 10. Estimated Cost of Operating and Maintaining Nuclide-Source Installations

Item		3-kw	5-kw	30-kw	60-kw
1. Direct Labor at \$3.00 per Man-Hour ^a		\$36, 000/yr	\$36, 000/yr	\$36, 000/yr	36, 000/yr
2. Overhead at 100%		36, 000/yr	36, 000/yr	36, 000/yr	36, 000/yr
3. Source Replenishment, Including Preparation and Transportation Cost ^b	Co60	23, 900/yr	43, 000/yr	176, 000/yr	290, 000/yr
	Cs137	9, 500/yr	16, 000/yr	68, 500/yr	124, 000/yr
	ZirNob	120, 000/yr	160, 000/yr	600, 000/yr	1, 200, 000/yr
4. Miscellaneous Parts and Utilities ^c		900/yr	900/yr	1, 500/yr	3, 000/yr
5. Total Annual Operating and Maintenance Cost	Co60	96, 800/yr	116, 900/yr	249, 500/yr	365, 000/yr
	Cs137	82, 400/yr	89, 000/yr	142, 000/yr	199, 000/yr
	ZirNob	192, 000/yr	232, 900/yr	673, 500/yr	1, 275, 000/yr
6. Operating and Maintenance Cost per Kilowatt-hour Produced ^d	Co60	\$5. 40/kwh	\$3. 90/kwh	\$1. 40/kwh	\$1. 00/kwh
	Cs137	4. 60/kwh	3. 00/kwh	. 80/kwh	. 60/kwh
	ZirNob	10. 70/kwh	7. 75/kwh	3. 75/kwh	3. 55/kwh

- Assumes 2 equivalent full-time personnel to perform operating, maintenance, and health-physics functions
- Assumes source allowed to decay to 90% of initial strength (100% of rated output) before replenishment. On this basis, replacement schedules are 12.5, 2.2, and 330% per year for Cobalt-60, Cesium-137, and ZirNob, respectively.
- Allows \$0.15 per hour for 3-kw and 5-kw, \$0.25 per hour for the 30-kw and \$0.50 for the 60-kw, respectively.
- Based on an operating schedule of 6,000 hours per year.

Summary of Cost Analyses for Nuclide Sources

Table 12 - 11 summarizes the cost factors on nuclide sources, and develops a cost figure in terms of dollars per kwh. At a beam utilization of 50 percent, a \$1.00 per kwh is equivalent to 0.3 cents per megarad pound, or 0.03 cents per pound of food treated at a low-dose "pasteurizing" level of 100,000 rad. As the efficiency of beam utilization increases, the cost per pound decreases in direct proportion.

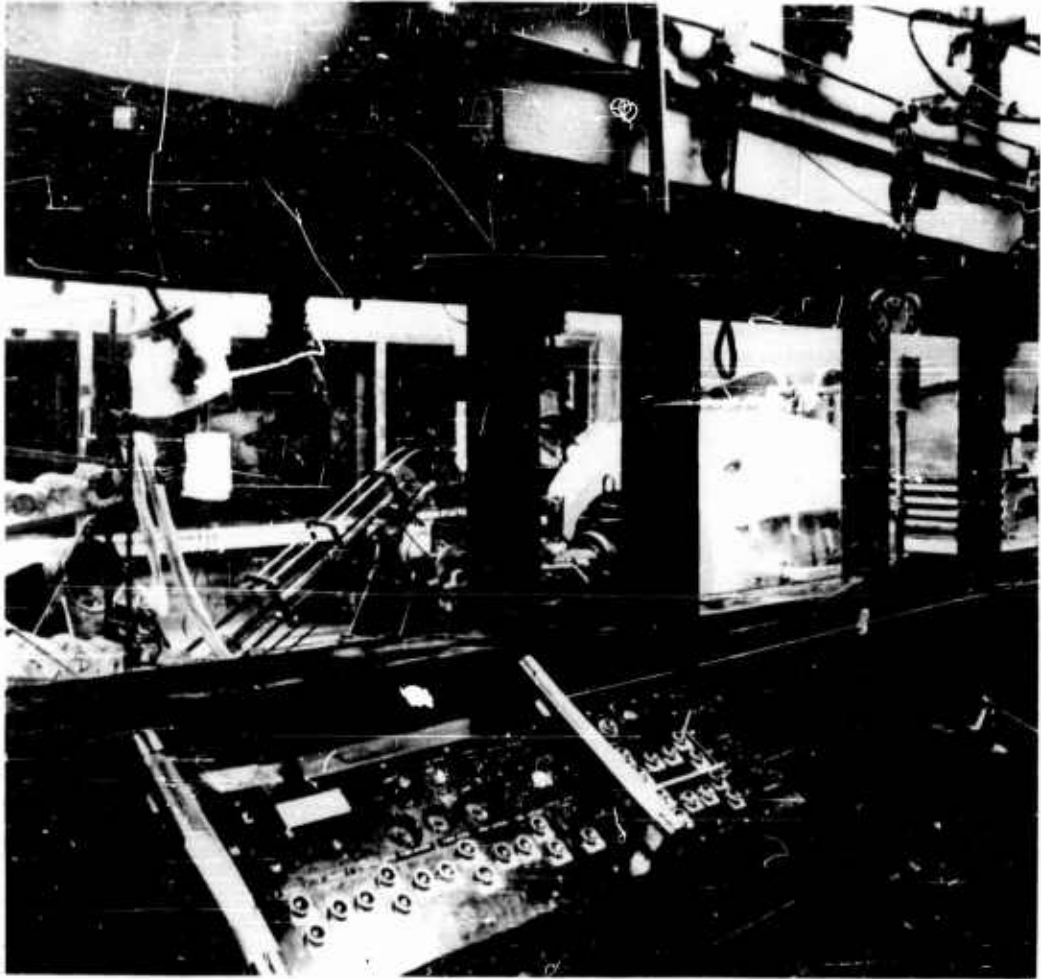


Figure 12-2. This experimental Food Irradiation Facility at Dugway Proving Grounds utilizes spent-fuel elements in air.

TABLE 12 - 11. Summary Cost Analyses of Nuclear Sources^a

	Cobalt-60					
	3 Kw	5 Kw	30 Kw	60 Kw	3 Kw	5 Kw
1. Nuclide cost	\$ 188,000	\$ 315,000	\$1,260,000	\$2,015,000	\$ 315,000	\$ 506,000
2. Source preparation	12,600	21,000	126,000	252,000	121,600	202,000
3. Shipment (1000 miles)	2,500	4,200	25,200	50,400	12,200	20,000
4. Installation	<u>120,000</u>	<u>200,000</u>	<u>300,000</u>	<u>480,000</u>	<u>120,000</u>	<u>200,000</u>
5. Total capital investment	323,100	540,200	1,711,200	2,797,400	558,800	929,000
6. Depreciation (10-yr, straight-line)	32,300	54,000	171,100	279,700	55,900	92,900
7. Operation and maintenance (see Table 12-10)	<u>96,800</u>	<u>116,900</u>	<u>249,500</u>	<u>365,000</u>	<u>82,400</u>	<u>89,000</u>
8. Total annual cost, <u>excluding</u> return on investment	129,100	170,900	420,600	644,700	138,300	181,900
9. Cost per kilowatt-hour produced, <u>excluding</u> return on investment	\$7.20/kwh	\$5.70/kwh	\$2.35/kwh	\$1.80/kwh	\$7.70/kwh	\$6.10/kwh
10. Provision for return on investment (at 10% of total capital investment)	32,300	54,000	171,100	279,700	55,900	92,900
11. Total annual cost, <u>including</u> return on investment	161,400	224,900	591,700	924,400	194,200	274,800
12. Cost per kilowatt-hour produced, <u>including</u> return on investment	\$8.90/kwh	\$7.50/kwh	\$3.30/kwh	\$2.55/kwh	\$10.80/kwh	\$9.15/kwh
a. Based on an operating schedule of 6000 hours per year						

Cobalt-60		Cesium-137				Zirconium		
30 Kw	60 Kw	3 Kw	5 Kw	30 Kw	60 Kw	3 Kw	5 Kw	30 Kw
\$1,260,000	\$2,015,000	\$ 315,000	\$ 506,000	\$1,825,000	\$2,920,000	\$ 37,000	\$ 61,000	\$182,000
126,000	252,000	121,600	202,700	1,216,000	2,432,000	-	-	-
25,200	50,400	12,200	20,300	121,600	243,200	-	-	-
<u>300,000</u>	<u>480,000</u>	<u>120,000</u>	<u>200,000</u>	<u>300,000</u>	<u>480,000</u>	<u>120,000</u>	<u>200,000</u>	<u>300,000</u>
1,711,200	2,797,400	558,800	929,000	3,462,600	6,075,200	157,000	261,000	482,000
171,100	279,700	55,900	92,900	346,300	607,500	15,700	26,100	48,200
<u>249,500</u>	<u>365,000</u>	<u>82,400</u>	<u>89,000</u>	<u>142,000</u>	<u>199,000</u>	<u>192,900</u>	<u>232,900</u>	<u>673,500</u>
420,600	644,700	138,300	181,900	488,300	806,500	208,600	259,000	721,700
\$2.35/kwh	\$1.80/kwh	\$7.70/kwh	\$6.10/kwh	\$2.70/kwh	\$2.25/kwh	\$11.60/kwh	\$8.65/kwh	\$4.01/kwh
171,100	279,700	55,900	92,900	346,300	607,500	15,700	26,100	48,200
591,700	924,400	194,200	274,800	834,600	1,414,000	224,300	285,100	769,900
\$3.30/kwh	\$2.55/kwh	\$10.80/kwh	\$9.15/kwh	\$5.20/kwh	\$3.95/kwh	\$12.45/kwh	\$9.50/kwh	\$4.30/kwh

Cesina-137				ZirMob			
3 Kw	5 Kw	30 Kw	60 Kw	3 Kw	5 Kw	30 Kw	60 Kw
315,000	\$ 505,000	\$1,825,000	\$2,920,000	\$ 37,000	\$ 61,000	\$182,000	\$363,000
121,600	202,700	1,216,000	2,432,000	-	-	-	-
12,200	20,300	121,600	243,200	-	-	-	-
<u>120,000</u>	<u>200,000</u>	<u>300,000</u>	<u>480,000</u>	<u>120,000</u>	<u>200,000</u>	<u>300,000</u>	<u>480,000</u>
358,800	929,000	3,462,600	6,075,200	157,000	261,000	482,000	943,000
55,900	92,900	346,300	607,500	15,700	26,100	48,200	94,300
<u>82,400</u>	<u>89,000</u>	<u>142,000</u>	<u>199,000</u>	<u>192,900</u>	<u>232,900</u>	<u>673,500</u>	<u>1,275,000</u>
38,300	181,900	488,300	806,500	208,600	259,000	721,700	1,369,300
.70/kwh	\$6.10/kwh	\$2.70/kwh	\$2.25/kwh	\$11.60/kwh	\$8.65/kwh	\$4.01/kwh	\$3.80/kwh
,900	92,900	346,300	607,500	15,700	26,100	48,200	94,300
,200	274,800	834,600	1,411,000	224,300	285,100	769,900	1,463,600
.80/kwh	\$9.15/kwh	\$5.20/kwh	\$3.95/kwh	\$12.45/kwh	\$9.50/kwh	\$4.30/kwh	\$4.10/kwh

Visualizing the future potential of radio nuclides, considerable advances in reactor technology may provide a basis for still lower production costs for Cobalt-60. Suggestions have been made for the use of cobalt as a "flux flattener" in power reactors which could foreseeably lower the cost to the 10-to 15-cent per curie range.

The long half-life of Cesium-137 makes it attractive for lease rather than outright purchase. A rental charge of \$20,000 per year per megacurie has been suggested which could lower the Cesium-137 user cost to 2 cents per curie per year.⁴

During the past five years, both North American Aviation, Inc.⁶ and Oak Ridge School of Reactor Technology^{7, 8} have explored the potential of designing a reactor which could irradiate production quantities of food. The homogeneous type reactor and an irradiation system involving the activation of a salt solution in the blanket of a heterogeneous reactor were investigated.

Fission gases from a 20-megawatt homogeneous reactor were studied in detail. The gases separated would be primarily D₂O vapor, D₂ and O₂ with traces of Xe and Kr fission gases. Assuming an optimum gamma power of 50-kw, a 25 percent useful absorption in the food, a radiation cell cost of \$445,000 and a food handling system of \$208,000, processing costs were obtained as shown in the following table:

TABLE 12 - 12. Estimated Gamma Processing Costs for 50-Kw Homogeneous Reactor

	3.5 x 10 ⁴ Rad	Exposure 10 ⁵ Rad
Annual through-put (at 90% plant factor)	2.40 x 10 ⁹ lb/yr	8.42 x 10 ⁸ lb/yr
Capital Costs ^a	0.0041¢/lb	0.0116¢/lb.
Loss of electrical output (Electrical power reduction of 6%)	0.0010¢/lb.	0.0028¢/lb.
Total costs	0.0051¢/lb	0.0144¢/lb.

a. No credit given for power.

Neutron-activated indium was studied in a Materials Testing Reactor (MTR) solid-fuel type, with a thermal rating of 31-megawatts of which 2 percent was generated in the indium blanket solution. The gamma power of the plaque source was estimated at 915-kw of which 20 percent (approximately 18-kw) could be usefully absorbed. The estimated cost of the reactor was \$2,500,000 exclusive of the cost of the fuel elements. The estimated cost of the radiation cell and ancillary equipment was \$192,000, and the cost of the conveyor system \$173,000, making a total investment of \$2,870,000. The estimated processing costs, excluding reactor operating staff, is presented in the following table:

TABLE 12 - 13. Estimated Gamma Processing Costs for Indium-Activated Loop from 31-mw Heterogeneous Reactor

	Exposure	
	<u>6.2×10^4 Rad</u>	<u>10^5 Rad</u>
Annual through-put (at 90% plant factor)	1.99×10^9 lb/yr.	1.23×10^9 lb/yr.
Capital costs	0.0216¢/lb.	0.0349¢/lb.
Minimum reactor fuel costs (\$33/hr)	<u>0.0131¢/lb.</u>	<u>0.021¢/lb.</u>
Total Costs	0.0347¢/lb.	0.0560¢/lb.

Several reactors have been or are now being designed which employ sodium as the liquid coolant. A cost evaluation based upon the use of sodium from the SGR (sodium graphite reactor) provides a source with a strength of 1.16-megacuries and a gamma power of 28.4-kw of which 20 percent (approximately 6-kw) can be usefully absorbed. The estimated cost of the cell and associated equipment is \$407,000, and the estimate for the conveyor system and additional equipment \$296,000, or a total of \$703,000. The estimated processing costs, excluding the reactor operating staff, is presented in Table 12 - 14.

The North American study of reactor sources clearly indicated that the least expensive gamma source is the gases fission products from a homogeneous reactor.

TABLE 12 - 14. Estimated Gamma Processing Costs for SGR (Sodium Graphite Reactor)

	Exposure	
	1.5×10^4 Rad	10^5 Rad
Annual through-put (at 90% plant factor)	2.69×10^9 lb/yr	4.04×10^8 lb/yr.
Capital Costs	0.0039¢/lb	0.0260¢/lb

Summary of Radiation Cost Factors

In irradiation processing, as in any other method of preservation, the operating costs consist primarily of the materials consumed, amortization of capital investment, interest charges, maintenance, and labor. In the case of electron generators the material consumed is negligible and the interest charges are relatively small, but the maintenance and labor costs are relatively high. With nuclide sources the converse is true. The material consumed is more significant and the interest charges are high because of the larger initial investment. However, the maintenance and labor costs are relatively small.

Table 12 - 15 presents a ready comparison between the several types of sources, considered:

TABLE 12 - 15. Comparison of Radiation Cost Estimates (\$/kwh)
6,000 hours of Operation per year

Source Size	Type of Source			
	Electron Generator	Cobalt-60	Cesium-137	ZirNob
3-Kw	\$6.95	\$8.90	\$10.80	\$12.45
5 Kw	5.10	7.50	9.15	9.50
30-Kw	1.30	3.30	5.20	4.30
60-Kw	1.00	2.55	3.95	4.10

TABLE 12 - 16. Estimated Costs for Preservation of Food by Low-Dose Ion

Applications	Rad				
	Dosage (Rad)	3 KW			Thruput #/hr
		Thruput #/hr	COST - Electron Machines	\$/Ton Co-60	
Sprout inhibition	10,000	133,920	\$0.31/Ton	0.40/Ton	1,339,200
Trichinosis control	25,000	53,928	0.76/Ton	0.99/Ton	539,280
Insect disinfection of cereals and grains	50,000	26,784	1.55/Ton	2.00/Ton	267,840
"Pasteurization" of meat	100,000	13,392	3.10/Ton	3.98/Ton	133,920

a. Assuming a utilization efficiency of 50 percent



for Preservation of Food by Low-Dose Ionizing Energy^a

Radiation Sources								
3 KW			30 KW			60 KW		
Thruput #/hr	COST - Electron Machines	\$/Ton Co-60	Thruput #/hr	COST - Electron Machines	\$/Ton Co-60	Thruput #/hr	COST - Electron Machines	\$/Ton Co-60
33,920	\$0.31/Ton	0.40/Ton	1,339,200	.058/Ton	.148/Ton	2,678,400	\$.045/Ton	.115/Ton
33,928	0.76/Ton	0.99/Ton	539,280	.15/Ton	.37/Ton	1,073,560	.11/Ton	.28/Ton
16,784	1.55/Ton	2.00/Ton	267,840	.29/Ton	.74/Ton	536,680	.225/Ton	.575/Ton
3,392	3.10/Ton	3.98/Ton	133,920	.58/Ton	1.48/Ton	267,840	.45/Ton	1.15/Ton

of 50 percent

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CHAPTER 13

ECONOMIC FEASIBILITY

The major potential application for the use of ionizing radiation in the civilian food economy is centered around low-dose "pasteurization" processing. The competition will be between this preservation process, after which the foods may be stored at normal refrigerated temperatures; as contrasted to a quick-freeze process, after which the foods require continuous storage at below freezing temperatures. "Pasteurization" definitely appears to be competitive with quick-freezing, as borne out by this report, and substantiated by a study recently completed by Arthur D. Little, Inc.¹. Results of this study are summarized in Table 13-1.

Prevention of sprouting in potatoes, onions, and other tubers has been accomplished through small doses of radiation in the order of 10,000 to 15,000 rad. Although radiation does prevent sprouting, it also appears to interfere with the process of suberization, thus raising certain doubts concerning the technical feasibility of the process. With respect to the economic feasibility it would appear that the cost estimates for the radiation process would be very competitive with the alternative processes, i.e., chemical treatments and controlled-environment storage. Thus, the primary factor in determining the economic feasibility of commercial radiation of potatoes is resolving the technical problems encountered.

It has been estimated that losses, resulting from insect infestation of grain in the United States alone, amount to more than 300 million dollars per year. Because of this tremendous loss, and the small radiation dose required for disinfection, considerable interest has been focused on this potential application.

Radiation disinfection appears to be considerably more expensive than current methods of fumigation. The cost of fumigation has been estimated as low as 0.2 cents per bushel, which is considerably less than that currently envisioned for radiation processing. Another consideration is that losses incurred from insect infestation are greatest in storage and farm areas. Therefore, costly radiation facilities would have to be installed permanently at large storage points or in mobile units for rural areas, thereby increasing the cost for using this process.

TABLE 13 - 1. Comparative Costs of Canning, Freezing, and Irradiating Meat^{a 1}

<u>Cost Elements</u>	<u>(¢/lb) Irradiating Costs^b</u>		<u>Freezing^c Costs (Plate Freezers)</u>
	<u>Electron Accelerator</u>	<u>Cesium-137</u>	
	<u>10⁵ rad</u>	<u>10⁵ rad</u>	
Raw Material	Same for all Processes		
Preparation for Processing			
Processing	0.33	0.62	0.32
Packaging	2.19	2.19	2.19
Transportation ^d	1.95	1.95	2.10
Storage ^e	<u>0.39</u>	<u>0.39</u>	<u>0.42</u>
Total	4.86	5.15	5.03

a. Production basis: In all cases, 43,200,000-lbs. are produced each year. Freezing costs are based on an 8-hour day, 300 days per year. Irradiation costs are based on 9,000-lb. processed per hour, 16 hours per day, 300 days per year.

b. The costs of radiation processing are based on the following costs per kilowatt-hour emitted from the source:

- (1) 2.26 kilowatt electron accelerator (10⁵ rad dose): \$11.40
- (2) 68 kilowatt electron accelerator (3 Megarad dose): 0.95
- (3) 2.26 kilowatt Cesium-137 source (10⁵ rad dose): 19.15
- (4) 68 kilowatt Cesium-137 source (3 Megarad dose): 6.30

In all cases a cost of 0.14-cent per pound (separately estimated) was added to cover nonsource direct labor and overhead, and amortization of the building and conveyor system.

c. Freezing costs were obtained from producers in the field.

d. Transportation figures were based upon costs from Chicago, Ill., to San Francisco, Calif.

e. Storage costs are estimated for private facilities.

Cost estimates become competitive only when considering sources of relatively high power outputs. Utilizing these high-power sources would provide rates of production which would not be feasible for use on individual farms or in government storage facilities. Thus, the greatest potential appears to lie with the miller, where large volumes of grain could be handled. However, infestation is not considered a major problem for the miller; therefore, it is difficult to identify economic incentives for this method of processing.

One very large potential is in grain elevators where insect infestation is prevalent. Disinfestation processing on large volumes of grain and flour could be performed when necessary during storage; also at ports of debarkation, simultaneously with loading grain for transit by truck, rail, or water for domestic or overseas shipment.

Another significant application lies in its potential for controlling trichinosis and other food-borne parasites. The relatively low dose requirements (in the order of 25,000 rad) makes this process appear economically feasible. Although the costs are relatively low, the fact that irradiation processing substantially reduces food-borne diseases would more than justify the cost. Thus, the use of ionizing radiation for this application will be determined primarily by public health aspects, rather than cost factors.

"Pasteurization" of fruits and vegetables has been extensively investigated and some technical problems still confront food technologists. Interest is generally centered upon the use of electron treatments inasmuch as gamma radiation, due to its treatment depth, often causes undesirable changes within the product.

It is difficult to figure accurate savings, if any, for irradiation-plus-refrigerated-storage, as compared with quick-freezing-plus-frozen-storage for fruits and vegetables. It would appear that this process may be economically feasible particularly for extending the shelf-life of fruits and vegetables which are not adaptable to quick-freezing methods.

"Pasteurization" appears to have significant applications for use in conjunction with conventional processing, especially for perishable fruits and vegetables. For example, low-dose irradiation treatments prior to canning and freezing could (1) extend the holding time of large quantities of fresh fruits and vegetables, thereby reducing losses due to spoilage; and (2) reduce the bacterial flora, thereby decreasing the thermal requirements for subsequent canning operations. The monetary savings thus provided appear to make both applications economically feasible.

"Pasteurization" of meat, poultry, and sea food products has received more intensive research than any other area of food irradiation. Although some technological factors are still under careful investigation, it would appear that many items will be well received after processing with "pasteurization" levels in the order of 100,000 to 300,000 rad. It must be realized, however, that food processors are confronted with a highly competitive market and a very small margin of profit. Thus, it would appear that in most cases processors could not adopt a "pasteurization" process which would cost more than 0.5 cent per pound. Inasmuch as current estimates fall well within this cost figure, this process offers great potential for "pasteurization" preservation of meat products. With the solution of certain technological problems, a relatively large portion of the fresh and frozen meat markets could be captured, at least in part, by the introduction of "pasteurizing" preservation processing.

Accurate technical and economic feasibility analyses can be made only after gaining operational experience in food processing pilot plants using ionizing radiation. The U. S. Army Quartermaster Corps is paving the way for the emergence of such data by erecting the Quartermaster Radiation Laboratory at its Research and Engineering Center at Natick, Massachusetts. This Laboratory will consist of a 24-million electron volt linear accelerator, a Cobalt-60 source of approximately 1-million curies, and a food preparation laboratory adequate to support the nuclear components. Groundbreaking ceremonies are scheduled for May 1961, and it is planned to have the Laboratory ready for occupancy in the summer of 1962. The facilities of this laboratory will be made available to other governmental agencies in support of their food irradiation programs. It is anticipated that industry may collaborate in using these facilities in designing processes for the preservation of specific foods by use of ionizing energy.

Inasmuch as an adequate civilian production base will be required to support the commercial utilization of radiation "pasteurization", American industry will be further encouraged through continued cooperative efforts of Government and industry. The next five years should truly determine whether low-dose "pasteurization" processes are economically feasible for the preservation of food.

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PART VI

POTENTIALITIES OF RADIATION PRESERVATION OF FOOD

Programs on Food Radiation Preservation are continuing on a national and international basis. It would be appropriate for the United States, as the leader of food production, to continue its position of leadership in this advanced concept of food preservation.

Significant progress has already been made by the Quartermaster Corps, and it is a well-known historical fact that requirements for military purposes have repeatedly been the basis for benefits to the civilian economy.

This is most clearly demonstrated by the success of Appert in 1809 in preserving foods for Napoleon's Army by keeping foods in boiling water for varying lengths of time. Last year, the sales of canned foods in this country amounted to 4.8 billion dollars.

Another instance is the fact that the U. S. Army spearheaded the utilization of dehydrated foods, not only for military use but for popular acceptance. Many of these items now stock the civilian super-markets and other retail stores.

It is confidently expected that the Army's efforts in developing processes for the preservation of foods by ionizing energy will meet with similar rewarding experiences. This may be true especially for low-dose radiation preserved foods where extension of shelf-life is a significant factor.

It is anticipated that this new method of food preservation will have potentialities in domestic and also international economies. Illustrative examples of potential benefits include:

Decrease losses caused by food spoilage: Evidence proves that irradiation processing extends the useful life of many perishable as well as staple food items. This can effect a tremendous savings to food producers, distributors, marketers, and consumers. For example, it has been estimated that a 2-day extension in the transportation and shelf-life of strawberries and a similar extension in shelf-life of bread could effect a 50 percent saving in marketing losses.

Radiation pasteurization of pork sausages, bacon, hams and other meats prolongs the refrigerated shelf-life considerably. This will extend the merchandizing period.

Control of insect damage to cereal products, spices, dried fruits, nuts, dates, and similar commodities may level out market fluctuations and reduce storage losses.

The sprouting of potatoes, onions, and garlic can be inhibited, thereby extending the period for merchandizing.

It is also conceivable that central preparation of precut irradiated meats will be encouraged at packing houses. This may diminish the cost for refrigerated facilities and skilled butchering at the retail level.

Control of food-borne and plant diseases: The effectiveness of ionizing radiations in destroying helminths, such as trichina worms in pork, has been established. It is expected that the same order of low-dose treatment would control flukes in fish. Preliminary pasteurization studies have given successful results with salmonella in eggs. The tubercle bacillus in infected cattle products also appear susceptible to control by reasonable doses of radiation. The use of ionizing radiation may reduce the bacterial count in the holds of fishing vessels in much the same manner as ultraviolet light reduces bacteria in the air. By this means, the vessel may be able to fish for longer periods of time, and longer distances away from home port. It appears, therefore, that contributions to the control of food-borne diseases may be expected from the ionizing processing technique.

The location of radiation sources at specific points along quarantine borders may combat the spread of plant diseases. The golden nematode in potatoes grown in certain areas of this country, or the fly in fruits grown in others, are typical of this class of disease.

Expand world markets: Most of the protein-deficient and hungry peoples throughout the world are not supported with adequate refrigerated transportation and storage facilities. When fresh meats are made available from other countries, the distribution away from the sea coasts is difficult. Irradiated raw foods, on the other hand, can be shipped without refrigeration. This raises the humanitarian hope that selected meats and fish can reach destitute peoples thousands of miles inland.

Because of insect infestation, tropical fruits are presently quarantined against entry into many countries. The radiation treatment promises to control the deeply-imbedded larvae without damaging the fruit. These fruits will probably be permitted across the quarantine barriers. There is also the possibility that the cold storage life of

certain fresh fruits can be lengthened significantly. This will extend their shipping radius and marketing zones.

Improve canned foods: A large factor contributing to the taste and texture of conventionally-canned foods is the long heating required. It is conceivable that heat sterilization can be replaced by radiation processing for selected foods, especially meats. The contents can then be heated to the optimal point, taking into account the subsequent re-warming in the family kitchen. For pasteurized foods, recent findings showed that the heating time as well as the temperature can be significantly decreased by a prior mild dose of irradiation. The resulting Danish ham (normally distributed under refrigeration) reportedly was considerably improved in quality.

Extend "quick-serve" foods: One of the recent lines of popular food items introduced in the supermarket is the so-called "brown-and-serve" rolls. These are sold in the partially baked condition. When ready for use, they need only to be taken from the refrigerator, placed in the oven for a few minutes for browning, and served. The irradiation process makes possible the extension of this concept to "brown-and-serve" chicken, beef, pork and other roasts, with the added advantage that, in the interim, they need not be kept in the refrigerator.

Improve logistics: It has been the Army's policy to feed combat soldiers perishable subsistence as soon as combat conditions warrant. The morale advantage of this is beyond question. The refrigeration capacity to support this policy is enormous and becomes impractical under modern concepts of mobility. Perishable foods preserved by ionizing energy would provide the capability of supplying fresh-like subsistence requiring a minimum of refrigeration support.

Support the Food-for-Peace program: This food preservation process could have a significant impact on supporting the President's Food-for-Peace Program, by preventing or limiting the vast waste of food grains and other commodities, which in some friendly nations approaches 50 percent of their total production.

Feed mass populations under national emergency conditions: It is conceivable that a reserve of irradiated foods could be the sole means of feeding large masses of civilian populations as well as military forces under disaster and national emergency conditions. For example, under atomic warfare, normal power sources may not be available for processing, transporting, and refrigerating foods. Stocks of frozen and perishable foods would soon become inedible whereas irradiated food items could be stored for extended periods of time without refrigeration.

Support space travel: Two essential characteristics of materiel for space travel are reliability and minimal weight. It is envisioned that irradiated foods will play a key role in fulfilling its food requirements. Without the need for refrigeration, high quality irradiated meat items can be provided. Fresh fruits, the shelf-life of which has been extended through irradiation, can be resupplied on a regular basis. Some vegetables may be grown locally in the space habitat as an adjunct to oxygen regeneration.

CONCLUSIONS

Considering the impact of these potentialities, industry, educational institutions, and governmental agencies are encouraged to continue their coordinated research and development efforts directed toward further advancing the technology for radiation preservation of foods. This will enable the food production lines of tomorrow to benefit from both sterilization processing, for long-term preservation without refrigeration; as well as "Pasteurization" processing, for extending the safekeeping of perishable foods.

